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THE DEPTH AND TWOFOLD CHARACTER OF EARTHQUAKE ORIGINS[1]

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ABSTRACT

A new method for determining the depth of origin of earthquakes is a simplification of the Dutton method, by which it is made more generally applicable. The result of the application of this method to the Italian record is reviewed and compared with that obtained from long-distance records. A comparison of these two sets of figures leads to important conclusions regarding the distinctness and connection of the earthquake which can be felt and the disturbance which gives rise to the long-distance records.

The word "earthquake," at the present day, has acquired a twofold meaning: it is still in common use in the old-fashioned sense of a quaking of the solid earth, which can be felt and may cause damage, but it is also used, in a more modern sense, for one of those disturbances which cannot be felt but can be registered by sensitive instruments of suitable construction. The latter is more especially a scientific usage, though the word finds its way into the newspapers in this sense, to the mystification of the ordinary reader, and the word "seismology" has come to be attributed to the study of these disturbances in an increasing degree, to the exclusion of its original meaning of the study of the disturbances which could be felt. The usage has some justification in the fact that these unfeelable dis-

[1] Address delivered in opening a Geophysical Discussion, held in the rooms of the Royal Astronomical Society, London, on February 5, 1926.

turbances first attracted attention through the fact that they were, in some cases, obviously connected with earthquakes which had been of destructive violence at places far away. When instruments became more generally established, and it was found that the disturbances which could be directly connected with great earthquakes were far outnumbered by others for which no such connection could be traced, it was assumed that these were manifestations of great earthquakes, in the original sense of the word, which would otherwise have remained unknown, because the center of origin lay under the sea, or in those wilder parts of the earth from which no news of such occurrences could come. It has, in fact, been generally accepted that the two forms of earthquake are essentially identical, differing only in the magnitude of the original disturbance and the distance from the place where it originated, but this is in reality merely an assumption, which has not ever been seriously established, or even tested. In what follows I propose to outline an investigation which seems to have an important bearing on this question and to show that the things which are each described by the same word, though identical in as far as they are manifestations of some form of elastic wave motion, are, with a very few exceptions, very different as regards their origin.

A fundamental element in this discussion is the depth of origin of the disturbance. So far as the long-distance records of the unfelt wave motion are concerned, much work has been done of late years, and on this point I have nothing new to add, but it is otherwise with the earthquake which can be felt. Various methods of deducing the depth of origin have been proposed, from that of Robert Mallet, through the methods depending on the recorded time of occurrence, to that of Major C. E. Dutton, based on the decrease of violence of the shock with increasing distance from the origin, but they all suffer from the common defect that they are only applicable, in practice, to a small number of shocks, which must all be classed as great, and, therefore, not representative of the average earthquake. What is needed is some simpler method by which the depth of origin can be estimated, if only approximately, in the case of the numerous minor shocks, of which the depth of origin has long been recognized as being small, though it has not been possible to express

this numerically. This seems to be possible of attainment in a very simple manner, which has been reached by a modification, and simplification, of the Dutton method of determining the depth of origin. As the method is a new one some description is necessary, but, as a detailed treatment of the subject will be published,[1] it will not be necessary to do more than indicate the general principles and final result.

The method, at the outset, depends on the postulate that the intensity of wave motion, using the word in the physical sense, as measured by the amount of energy transmitted across a unit area in a unit of time, will vary inversely as the square of the distance from the origin. In a perfect medium, in which there is no absorption of energy, and with a simple form of wave motion, which does not vary in character during transmission, this would not be an assumption, but an inevitable consequence of the fact that the same total amount of energy would be transmitted across the successive wave fronts in equal intervals of time and, since the total area of the wave front increases directly as the square of the distance from the origin, the amount transmitted across each unit of area would vary inversely as the square of this distance. In nature neither of the supposed conditions occurs, but it will be convenient to examine first the consequences which would follow if the ideal conditions existed, and then to consider what modification is made necessary by the conditions actually existing.

If m and n represent the numerical values of the intensity at the epicenter and at some other point, d the distance between these two points, and h the depth of the origin below the epicenter, then simple trigonometry gives the equations

$$\sqrt{\frac{n}{m}}=\sin e$$

and

$$h=d \tan e.$$

In these formulas an angle has been introduced, which would be the angle of emergence if the wave paths were straight lines; it is not,

[1] *Quart. Jour. Geol. Soc.*, Vol. LXXXII, Part I (1916).

however, used in this sense, but merely as an imaginary angle, brought in to simplify calculation, for it would be easy to frame an equation which would express the value of h in terms of n, m, and d without introducing any trigonometrical ratio, but the expression would be cumbrous, whereas, in the form given, it is simple and easy to use.

The use, however, is subject to two limitations. Firstly, it is only applicable where the origin is simple and of small dimension, in comparison with the size of the disturbed area, for if the earthquake has more than one center of origin, and such cases do occur, the formula is obviously inapplicable; secondly, it does not hold good when the depth of origin is very small, for then the proximity of a free surface introduces complications which lead to the real depth's being less than that deduced from the formula.

With these limitations the method still retains great practical utility, for there are many earthquakes of which the maximum violence at the epicenter, in terms of one of the so-called scales of intensity, and the area over which the shock could be felt, are both known, and if it is possible to attach a numerical value to the intensity, in the sense used in the formula, of these two degrees of violence, we have the data necessary for calculating the depth of origin. Moreover, as the argument is from a ratio, it is not necessary to have absolute values, so long as the ratio of the two figures is correct.

The first step, therefore, is to examine whether such numerical values are actually attainable, and for this it is necessary to examine the expression representing intensity. This is usually written in the form

$$I=\frac{2\pi^2a^2VD}{t^2}$$

where V represents the velocity of transmission of the wave motion, D the density of the medium, a the amplitude of movement, and t the period of the wave motion. But this formula may also be written as

$$I=\frac{VD}{2}\times a\times\frac{4\pi^2a}{t^2}.$$

In this form the third term represents the maximum acceleration of the wave motion, the first term reflects the well-known fact that two

localities, close by each other but differing in the character of the subsoil, may experience different degrees of severity of the same shock, yet when, instead of dealing with isolated observations, we deal with a large number of records, these differences will disappear in the average, and the term may be treated as a constant, with the result that the intensity becomes directly proportional to the product of the amplitude and maximum acceleration of the wave motion.

For determining these elements, instrumental records cannot be used, since suitable instruments have not been established, nor is it likely that they ever will be, in sufficient numbers for the records to be generally available, and we have to fall back on the so-called scales of intensity. These, in their origin, were purely empirical. It was recognized that earthquakes varied greatly in character, from those which could barely be noticed by a few favorably situated persons, to those which laid cities in ruins, and when experienced observers began to classify them it was recognized that those which produced certain effects were evidently greater disturbances than those which did not, and so a grouping in successive degrees of severity was made. Of these scales only the Rossi-Forel and the Mercalli have remained in general use.

With the advance in knowledge of the nature of the earthquake it was found that the criteria by which the different degrees were distinguished were almost wholly the effect of acceleration, and attempts have been made at different times to determine the numerical values of the limiting accelerations of each degree. These were reviewed, and one or two modifications introduced, and the limiting values finally adopted are given in the third column of the tabular statement printed in Table I, the first two columns showing the degrees of the Rossi-Forel and Mercalli scales to which these limits refer. In using these figures it must be remembered that not only are the estimates approximate, but the degrees themselves are indefinite, so that it is not always possible to decide the degree to which a shock should be ascribed and different values may be estimated by different workers; for instance a shock which might be classed by one recorder as V°, M., might by another be regarded as either VI° or IV°, especially if it really lay near the limit of the two groups, and the corresponding acceleration might be outside the

limits of 110 and 150 mm. / sec.^{2}; but these uncertainties largely disappear when an average of a number of shocks is used, and then V°, M., may be taken as equivalent to a maximum acceleration of the wave motion, lying between the limits given in Table I.

The amplitude of displacement is known with much less certainty than the acceleration. On the whole, the two decrease together; an

TABLE I

SHOWING THE ADOPTED LIMITING VALUES OF MAXIMUM ACCELERATION, DOUBLE AMPLITUDE, AND RELATIVE INTENSITY OF WAVE MOTION FOR DIFFERENT DEGREES OF THE ROSSI-FOREL AND MERCALLI SCALES, AND THE FACTORS USED IN DETERMINING THE DEPTH OF ORIGIN

DEGREES		ACCELERATION		INTENSITY		
R-F	M.	Max. Accel. (mm./sec.)	Factor	Double Ampl. (mm.)	Relative Intensity	Factor
X.....	X	2,000	.100	50	100,000	.007
X.....	IX	1,300	.125	32	41,600	.011
IX.....	VIII	800	.160	20	16,000	.018
VIII.....	VII	300	.267	8	2,400	.046
VII.....	VI	150	.392	4	600	.092
VI.....	V	110	.471	3	300	.124
V.....	IV	80	.577	2	160	.198
IV.....	IV	60	.707	1	60	.302
III.....	III	40	1.000	0.5	20	.577
II.....	II	20	.....	0.25	5	.....

acceleration of 2,000 mm. / sec.,^{2} in a destructive earthquake, goes with an amplitude of 25 to 50 mm., or more, while an acceleration of 20 mm. / sec.^{2} will have a mean amplitude of about 0.125 mm., but there is no recognizable relation between the two. The amplitude, in fact, is subject to a very wide variation in amount; thus for 20 mm. / sec.^{2} of acceleration, accepted as in general the lower limit of sensibility, though lower values have been recognized as sensible in special circumstances, the amplitude may, seemingly, vary be-

tween the extreme limits of about 0.01 mm. and 0.40 mm. The same is, proportionately, true for higher accelerations, and all that could be done was to determine, from recorded observations and a certain amount of interpolation, the probable mean value of the amplitude corresponding to different values of acceleration. These values are given in the fifth column of Table I, in the form of the double amplitude, or range of movement, this being adopted as being the form more usually used, and as avoiding fractional figures in the product of acceleration and amplitude, given in the sixth column of the table.

The final column gives the factors by which the radius of the disturbed area must be multiplied to obtain the depth of origin of an earthquake which exhibits the corresponding degree of acceleration at the epicenter, but before the factors in this column can be used it is necessary to consider the loss of intensity due to causes other than the increasing area of the wave front. One of these is the absorption of energy during transmission of the wave motion; another, and probably the most important, is the effect of dispersion. In the argument at the outset it was presumed that the wave motion was of a simple character so that there would be no difference in the rate of transmission of the different parts of the disturbance, but this is by no means the case in reality. It is well known that the total duration of an earthquake increases outward from the epicenter until a maximum is reached, and then progressively decreases; the decrease is due to the general enfeeblement of the shock, so that a smaller and smaller proportion of the whole disturbance retains sufficient power to make itself felt, but the increase can be due only to the fact that the wave motion is of a complex character, the different elements of which have different rates of transmission. Other possible sources of loss of intensity are conceivable, but it is not possible, as yet, to estimate separately the amount of each, though it is possible to form an approximate estimate of the combined effect of all, and, as it may be inappropriate to use the word "absorption" for an effect in which it plays but a part, I shall use the expression "loss of intensity" to describe the combined effect of all those causes by which the intensity is diminished, apart from the decrease in intensity due to increase in the total area of the wave front.

The only estimates which have been published refer to the surface waves of long-distance records, and the coefficient of loss, amounting to about 0.0003 per km., is so small that its effect, over the distance concerned in those earthquakes which can be felt, might be treated as negligible, if the coefficient could safely be applied; but the character of the disturbance is so different, in the two cases, that this could not be assumed without proof, and it was necessary to examine the question anew. The method adopted was to use the isoseists of certain earthquakes, for which they had been worked out in detail; knowing the distances from the epicenter, it was possible to calculate what would be the ratio of decrease of intensity, on the simple assumptions adopted at the outset and to express this decrease in the form of a mean kilometric coefficient; it was also possible, using the figures in the sixth column of Table I, to calculate the actual mean kilometric coefficient of decrease, and the difference between these two gave the coefficient of loss of intensity.

The result of this comparison showed that the loss was by no means negligible, but of a magnitude which would very materially affect the calculation, and further that the rate of loss increased rapidly toward the surface. As a preliminary and necessarily approximate estimate the kilometric coefficient of this loss of intensity, apart from the decrease due to the square of the distance, may be put at about the following figures:

at depth 0 km. the coefficient of loss is about 0.5 per km.
at depth 1 km. the coefficient of loss is about 0.2 per km.
at depth 4 km. the coefficient of loss is about 0.1 per km.
at depth 10 km. the coefficient of loss is about 0.05 per km.
at depth 25 km. the coefficient of loss is about 0.02 per km.

It would, of course, be possible to introduce these factors into the equations for determining the depth of origin, but the calculations would be laborious, and the value of the result, in view of the uncertainty in the value of the coefficients, would be small. Search was, therefore, made for some other simpler method which would give sufficiently accurate results; a comparison was made between the observed decrease of acceleration and the calculated decrease of intensity, if loss of intensity is ignored, and this comparison showed that the difference between the two coefficients almost disappeared;

the error introduced by using a wrong measure practically cancels out the error due to the neglect of a material factor, with the result that we have a simple and easily applied method of determining the depth of origin with an error no greater, proportionately, than the uncertainty of the initial data.

Actually the coincidence is not complete and the difference differs in sign and amount at different depths; for very shallow origins the depth calculated in this manner may differ materially from the real depth—for instance, a true depth of about half a kilometer may appear as depths ranging up to over three kilometers, according to the degree of maximum violence at the epicenter—but this proportionately large discrepancy becomes much smaller at greater depths, the true depth remaining less than the calculated until a limit is reached, below which the reverse relationship holds good. It is not possible, as yet, to specify this limit of depth precisely, but it is somewhere about 10 km. below the surface, and from that down to about 30 km., the real depth is greater, though not materially greater, than the calculated one. Below about 30 km. the relation is again reversed, and the real depth is less than the calculated, but this group is of little interest, both on account of the very small proportion of shocks which seem to come from greater depths, and because a large proportion belong to the class having composite origin, to which the method is inapplicable.

We have, consequently, a very simple method by which the depth of origin of the earthquake can be determined, approximately, in that very large number of cases where the more elaborate and precise methods are inapplicable, and it is for the application of this that the factors given in the fourth column of Table I were computed. It must be remembered, however, that the method in its final form is purely empirical, and it is none the worse for that; empirical formulas are in constant use, and useful so long as no attempt is made to apply them outside the limits within which they have been shown to hold good, and this one gives a means of adding materially to the understanding of that very numerous class of moderate earthquakes which, so far, have baffled inquiry.

In the application of this new method use has been made of the very complete and detailed annual catalogues published by the

Italian Government. On examining these it was found that the records before 1897 could not be used, because the particulars of maximum degree of severity were seldom given, but from that date the information became fairly complete, up to the end of 1910; after this only the preliminary, abstract, lists were available. The period mentioned gave a total of 5,605 distinct shocks, which were subjected to examination and tabulated, with the result that over 90 per cent of them were found to have originated at depths of less than 5 miles, or 8 kilometers, below the surface, some 7 to 8 per cent at depths of 8 to 30 km., and about $1\frac{1}{4}$ per cent gave depths of over 30 km., but most of these, as has been mentioned, belong to the class of earthquakes having a composite origin, to which the method is inapplicable. These figures merely give a numerical confirmation to what was well known to all who have studied these earthquakes which can be felt; it has for long been obvious that these were prevailingly of very shallow origin, though no actual figure could be given to define this phrase. Now we can definitely say that at least nine out of every ten of them originate at a depth of less than 10 km., and predominantly at depths of about 4 or 5 km.

Turning to the long distance records we have, first, the study by Dr. L. Pilgrim of 10 distinct disturbances; the method is based on a comparison of the observed time of arrival with the tabular average time for the corresponding distance from the origin, and the depths of the origin determined by him are in 3 cases less than 100 km., the smallest being 50 km., and in 7 cases over 100 km., the greatest being 170 km.[1] Next we have the oft-quoted work of S. Mohorovičić, based on two earthquakes, of which he determined the depths of origin as about 25 and 45 km.,[2] the latter being one for which Dr. Pilgrim deduced a depth of 100 to 110 km. Then we have the work of the late Dr. G. W. Walker, who believed that some of these disturbances originated at depths of as much as 1250 km. below the surface,[3] and finally Professor H. H. Turner's researches, which deal with a much larger number of origins than those treated by other

[1] *Beiträge zur Geophysik*, Vol. XII (1913), pp. 363–483.

[2] *Ibid.*, Vol. XIII (1914), pp. 217–40; Vol. XIV (1916), pp. 187–98.

[3] *Phil. Trans.*, Series A, Vol. CCXXII (1921), pp. 45–56.

workers, and of which he has recently given an instructive summary.[1] According to this, the great bulk of the origins is grouped round about a depth of 200 km., a small proportion range down to depths of 600 km., being mainly grouped round a depth of 500 km., and a still smaller fraction of the origins is shallower, grouped principally round about 100 km.

Naturally none of these estimates pretends to exact numerical precision, but they are of an entirely different order of magnitude from those got for the earthquakes which can be felt. In the one case the depths are, with few exceptions, less, and markedly less, than 10 km.; in the other, also with a small proportion of exceptions, the depths are of the order of well over 100 km. and even of hundreds of kilometers. This difference in the depths at which the respective disturbances originate argues a corresponding difference in the cause of origin, yet it is certain that, in some cases though not demonstrably in all, there is a definite connection between the long-distance records and earthquakes which could be felt, and usually were destructive, in the region overlying the place of origin. There is evidently some connection between these two sets of origins, divergent as they are in situation, but before considering this question it will be useful to refer to two words the use of which will materially assist the discussion.

In 1908, when considering the geological bearings of the earth-movements which accompanied the Californian earthquake of April 18, 1906, it became apparent that the San Andreas fault, which had been regarded as the cause of the earthquake, though certainly by far the most important center of origin of the surface shock, was not the only one, and that there were other lesser, though still important, centers of origin. It appeared also that these separate centers of origin of the destructive surface shock were the secondary effect of a larger, more simple, and deep-seated disturbance, for which the name "bathyseism" was proposed.[2] At the time, I wished to coin a correlative term to designate the surface shock which originated directly from the origins of lesser depths, but scholars to whom

[1] *Geophys. Suppl. Monthly Notices, Roy. Astr. Soc.*, Vol. I (1923), p. 55.

[2] *Quart. Jour. Geol. Soc.*, Vol. LXV (1909), p. 14.

I submitted the question, though approving the correctness of the word bathyseism, objected to the suggestions made for designating the disturbance of shallow origin, nor could they suggest any term which would be regarded as correctly compounded. This matter was allowed to rest, for, at the time, it did not seem urgent; the surface shock was still the real earthquake, for which no specially distinctive name was yet required. Conditions have altered since, and it has become necessary to have a term correlative, while expressing a contrast, with the deep-seated bathyseism, and for this I propose to use the word "episeism," which, though wrongly compounded, is no more barbarous than most of the scientific terms in common use; it expresses at once the notion that the episeism lies above, and that it is borne upon, the bathyseism.

It is not possible to discuss the nature of the connection between these two, without opening up the whole question of the origin of earthquakes, but it may be useful to indicate one possibility, in illustration of the character of the relation between bathyseism and episeism. The surface shock, which can be felt, is generally regarded as due to fracture of the solid rock, which has been strained beyond its power of resistance; in the great majority of cases this seems to be a probable explanation, and it is a perfectly feasible one in the case of shocks which originate at depths of not more than a few kilometers from the surface, but it is hardly conceivable that fracture, such as comes within our experience, could take place in the conditions existing at a depth of a couple of hundred kilometers. At these depths a more probable explanation is a sudden change in the grouping of the chemical elements, accompanied by a change of bulk, for which we find the nearest surface analogy in an explosion. A phenomenon of this sort would give direct origin to elastic waves which would be transmitted outward to long distances, and at the same time the change of bulk would react on the surface rocks, setting up strains, and causing fractures, from which an independent surface shock, or episeism, would originate.

Accepting this distinction we have an explanation of the discrepancy between the estimates of depth of origin obtained from the study of long distance records, and of the sensible shock near the epicenter; the former would refer to the bathyseism, the latter to

the episeism, and of this conclusion there is specific support in two instances. The Californian earthquake of 1906 was elaborately investigated, and, from the variation in violence of the shock, Professor H. F. Reid concluded that the depth of origin was about 20 km.; at a later date Dr. L. Pilgrim, from the distant records, deduced a depth of about 140 km., and these two widely divergent estimates, both attained by what appears to be perfectly sound reasoning, can be reconciled if we remember that Professor Reid's refers to what has been defined as the episeism, while Dr. Pilgrim's is that of bathyseism. The second instance is the Indian earthquake of 1897; this occurred too early for distant records to be used, in determining the depth of origin, but I have recently had occasion to reconsider the original account of this shock, in the light of later advances in the study of earthquakes,[1] and have concluded that the depth of the bathyseism must have been of the order of 150 to 200 km., the episeism being clearly of shallow, and in many places zero, depth.

But this conclusion leads to a further one, that seismology is not one subject, but two subjects, differing so radically in the nature of the data with which they deal, and in the methods of dealing with them, that they become almost two distinct sciences, so distinct in fact, and requiring such a difference of temperament for successful study, that only very exceptionally could the same individual achieve mastery of both. The time seems, therefore, to have come for the difference to be recognized in a nomenclature which should at once express the distinctness of the two from each other, and the connection which exists between them as separate branches of the same stock. To some extent this has been done; we used to speak of the old and the new seismology, but the terminology has become out of date, for the new seismology has attained its majority, and seems inclined to usurp the title of its parent. A fresh nomenclature has become necessary, and for the later development, the study of the long distance records, and of the bathyseism, the word "teleseismology" comes naturally from the term teleseism, which is in actual use to designate either a seism record at a long distance from its origin, or one which gives rise to long distance records. From this, by analogy and contrast, the study of the episeism, or earth-

[1] To be published in the memoirs of the Geological Society of India, Vol. XLVI.

quake which can be felt, becomes "engysseismology," from the Greek word signifying "near by," for not only is the origin near to the surface, but the observations are necessarily confined to a distance from the epicenter which makes them near by, in comparison with the long distance record of the unfeelable disturbance.

It is now some four years since these terms were first proposed;[1] their utility, as expressing at once the distinction and relationship of the two seismologies, seems to become more obvious as time goes on, and the adoption of these, or some other words having the same meaning, would tend to greater clarity of thinking than exists at present, owing to the divergent senses in which the words "earthquake" and "seismology" are used.

[1] *Encyclopedia Britannica*, 12th ed., Vol. XXXII (1922), p. 390.

THE STRATIGRAPHIC SIGNIFICANCE OF SOLUTION IN ROCKS

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ABSTRACT

Solution has produced significant effects within rocks, especially within limestones, dolomites, and marbles. Formations have been reduced in thickness perhaps as much as 40 per cent or more in some instances. A solution residue has been introduced into the rocks which requires a stratigraphic interpretation quite different from that commonly assigned. Many puzzling claylike layers and films owe their genesis to subsequent alteration of the rock rather than to special conditions of sedimentation. Various odd structures, such as stylolites, originate from differential solution which occurred after the rock had hardened.

INTRODUCTION

Solution within rocks should be recognized as a significant process in explaining various types of stratigraphic peculiarities. Many ways by which it has modified and reduced rocks have been little suspected. That the origin of various phenomena in strata cannot be traced back to the birth of the sedimentary rock in which they are found is a fact continually attracting recognition among students of stratigraphy and sedimentation. Whereas, for example, early geologists attempted to explain nearly all perplexing features, such as stylolites, cone-in-cone, concretions, etc., in terms of special phases of sedimentation, it is now established that many phenomena, even other than those resulting from recognized diastrophism and metamorphism, are a result of changes which took place subsequent to the deposition and consolidation of the strata.

The unquestionable fact that solution within the rock mass is the vital factor in the development of stylolites has brought to the writer's attention the question of how significant has been *solution* in producing other effects which require consideration in the interpretation of geologic sections and the making of historical deductions. Recent chemical and field investigations by the writer on the nature and origin of stylolites strongly confirmed the idea that this feature is developed in special types of rocks by differential chemical

solution of the *hardened* strata, rather than developed in the soft, unconsolidated sediments at the time of, or shortly following, deposition.[1] Stylolites, thus, are one case of a secondary stratigraphic feature, produced by a secondary process—solution—in the already hardened strata. Inasmuch as comparatively little attention has been given to this type of solution work, certain geologic significances of it have been largely overlooked. In addition to having produced, under proper conditions, the peculiar stylolitic and related phenomena in rocks, the stratigraphic importance of the solution is primarily twofold, as follows:

1. A portion of the original rock has been removed and the beds consequently have been made thinner. Thus the apparently complete record of sedimentation is not represented in a given bed, and various peculiar relationships may have resulted.

2. Thin claylike films, or partings, have been developed within and between the beds as a residual product of the dissolved rock. Such are not original sedimentary layers, but such have been introduced into the rocks as partings subsequent to the deposition of the sediment.

It is the purpose of this paper to call attention to some significances of the above in the study of stratigraphy and in some interpretations of geologic history.

THE SOLUTION PROCESS REVIEWED

In order to present the type of solution work, with the importance of which this paper is concerned, the salient factors pertaining to the nature and origin of stylolites will first be reviewed.[2]

Prominent solution is restricted to carbonate rocks—principally to limestones, dolomites, and marbles. Stylolites are, with rare exceptions, limited to such types. They are not to be found in clastic rocks (excepting, perhaps, in occasional horizons with a high carbonate content), in igneous rocks, or in most types of metamorphic rocks. Although solution is slightly effective upon nearly insoluble

[1] Paris B. Stockdale, *Stylolites: Their Nature and Origin*, "Indiana University Studies," Vol IX, December, 1922.

[2] Full details on the nature and manner of origin of stylolites will not be presented here. Such can be obtained from the foregoing reference. An extensive bibliography is there given, and much literature on the subject is there reviewed.

materials, such as quartz—especially when long periods of time such as geology offers are available—the effect there is little as compared with that in the much less resistant rocks. The frequency of stylolites in limestones and marbles is, of course, well known.

Stylolitic phenomena result from a differential solution of the consolidated rock, under some pressure, on the two sides of a parting, such as a bedding plane, the undissolved portions of the rock on the one side fitting into the solution cavities opposite, the interfitting taking place slowly and gradually as solution continues. A normal clay-like substance is left as a residue from the dissolved rock. Most of this rests as a cap at the ends of the stylolites. The sides of the columns are fluted, striated, and even slickensided as a result of the slow movement involved.

Essential factors in the development of stylolites may be summarized as follows: (1) A first requisite is a rock which is differentially soluble. Most commonly limestones, dolomites, and even marbles are not uniformly resistant throughout. Evidence of differential resistance to solution of such rocks is strikingly presented in honeycombed weathering effects. (2) Ground waters, charged with carbon dioxide, must be present to act as the dissolving agent in producing stylolites. (3) Some sort of parting, along which water circulation is free and concentrated, is needed. This parting is most commonly a bedding plane, though it may be a crevice running in any direction —even a fault. It may be an unconformity. No original clay layer is necessary along the parting. (4) Pressure is needed to make stylolites. It may be static, resulting from the weight of the overlying rocks, or it may be lateral, dynamic pressure. The amount of pressure need not be great. (5) Sufficient amount of time must be allowed. Since variations of the foregoing factors occur, solution, therefore, produces effects with a great many differences.

A simple and ideal example to illustrate the development of stylolites will be presented without details. A bedding plane in limestone will be considered as the parting along which active solution occurs. Suppose the beds of limestone exhibit differential solubility and that the more soluble portions are regularly distributed, first on one side of the bedding plane and then on the other. The weak solution of carbonic acid would of course attack the less resistant zones,

soon producing an undulating parting (see Fig. 1, *A* and *B*). These undulations would gradually become more prominent as solution continued. In due time pressure becomes a significant factor. The

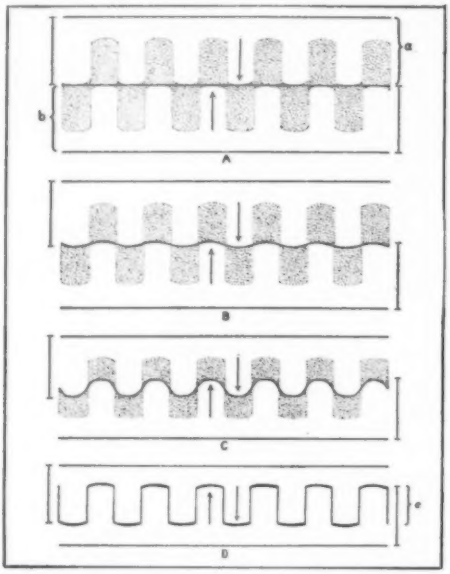

FIG. 1.—Diagram illustrating the development of stylolites from an ideal situation. The dotted areas are those to be removed by solution, representing slightly less resistant portions of the rock. In *A*, no solution has taken place. The limestone beds, *a* and *b*, are separated by an even bedding plane. A slight amount of solution has taken place in *B*, producing an undulating seam. Greater solution has taken place at the stage *C*, giving more pronounced undulations. Pressure is greatest at the crests and troughs of the undulations. A final development of columns is shown in *D*. A dark residue remains at the end of each column. The amount of thinning of the beds is indicated by *e*.

static pressure (resulting from the weight of the superincumbent strata in this example) is greatest on the crests of the undulations, and is least on the sloping sides. Since pressure is important in increasing the solubility of certain solids in liquids, the rock opposite the top and bottom surfaces of adjacent undulations will succumb to a greater rate of solution, producing (*a*) a deepening of the inter-

penetrating parts, (*b*) a further decrease in pressure (and consequent dissolving of the rock) on the sides of the undulations, and (*c*) a possible final development of vertical columns with a decided concentration of the pressure and accompanying solution at the ends (see Fig. 1, *C* and *D*). The insoluble constituents of the rock remain as a residue, most of which rests as a cap at the end of each stylolite, but some of which may be found as a thin film spread along the sides of the columns. Gradual movement of the hard columns past one another produces striations and slickensides on the sides.

The irregular and variable conditions in nature cause many departures from the ideal situation outlined above. No attempt will be made here to discuss the variations in the types of stylolites nor to review the abundance of evidence substantiating the theory that stylolitic features originate in hardened rock by solution and removal of material, and not in soft, plastic sediment by differential compression before consolidation. The prevalence of stylolites, originating in such a manner, indicates that solution is important in the modification of strata.

REDUCTION IN THICKNESS OF ROCKS BY SOLUTION

Inasmuch as the solution work under consideration leaves no cavities the strata are necessarily reduced in volume in proportion to the amount of material which has been dissolved and carried away. That rock material has been actually removed from the beds and that a part of the record of sedimentation is thus lost has not been commonly considered by geologists. Some special effects produced by such rock reduction and the criteria by which calculation of the amount of rock loss can be made will be briefly presented.

Special effects and their relation to rock removal.—Where stylolites have been developed rock removal was necessary to an amount equal at least to the length of the columns (see Fig. 1). Of course this was necessary to the making of the feature, since each column penetrates a place in the rock carved out by solution. Even adjacent stylolites, however, vary in length. This is not because of differing amounts of solution, but because of the fact that the ends of the now shorter penetrations have themselves succumbed to some dissolving, instead of all the removal being in the stone opposite the column ends and

on but one side of the original parting (see Fig. 2). Even subordinate penetrations on the ends of major columns may have resulted (see Fig. 2). It is possible that all the columns of a seam may have been attacked on the ends, and thus have had their growth in length retarded.

One is thus led to suspect greater thinning than that evidenced by the actual length of the individual stylolites. As a matter of fact it is possible that rather uniform solution might occur within the

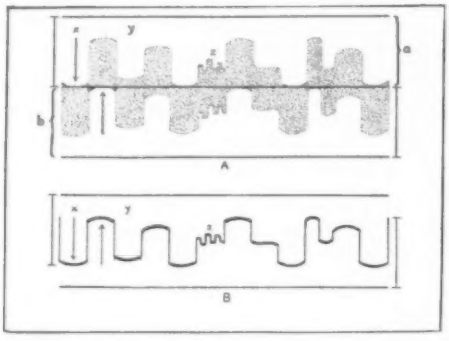

FIG. 2.—Diagram to illustrate irregularity in the length of stylolites and the required distribution of the solution to produce such. In *A* the two limestone beds, *a* and *b*, are separated by a normal bedding plane. The dotted portions are those to be removed by solution. The resulting stylolite seam is shown in *B*. Note that column *x* has a maximum length, there being no solution of the end of the column itself, whereas column *y* is shorter, since all the dissolving was not restricted to the opposite bed at this place. Minor stylolites superimposed upon a major column are illustrated at *z*.

rocks, either on one side or both sides of a parting, and the stylolite feature not develop, since the latter requires differential solution. In this case the best testimony to the solution would be the residual claylike seam (see Fig. 3). Furthermore, stylolite seams are occasionally undulating, especially in marbles. Such sutures may have begun along an irregular contact, but the undulations may have developed by a slightly greater amount of dissolving in the overlying rock, at the place of the upward curve in the seam, whereas the reverse was true along the downward directed curve (see Fig. 4). Above and

below such undulating seams may be found straight sutures, proving that the curving was not due to rock folding. Evidence that some layers have been almost entirely removed is seen in scattered remnants of well-marked horizons adjacent to undulating stylolite seams (see Fig. 5). May not some beds have been completely dissolved away, with nothing to testify to their existence? Evidence of similar rock destruction is seen in instances where but a fragment of a preexisting stylolite seam now remains spanning a curve in a major

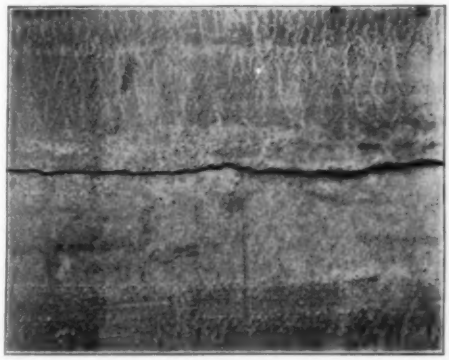

FIG. 3.—Photograph of a slightly undulating seam of black claylike residue, a product of fairly even solution between the beds of limestone. From a quarry of the Consolidated Stone Company, Dark Hollow District, Lawrence County, Indiana.

parting (see Fig. 5). Figure 6 shows another type of irregularity commonly found. Such examples as illustrated in Figures 4, 5, and 6 reveal the fact that the actual amount of material removed by solution may have been several times as great as that which the mere length of the columns themselves would seem to indicate.

Calculations of rock loss by solution.—To secure quantitative data on the thinning of strata the writer made a series of measurements in stylolitic rocks. In one case marble slabs representing an aggregate measure of about 24 feet, coming from Lower Mississippian quarries near Carthage, Missouri, were studied. Only the lengths of the columns of the seams, disregarding all such irregularities as those

of Figures 4, 5, and 6, were used in making first calculations of loss by solution. The results follow:

Amount of stone measured	284.0 inches
Number of prominent stylolite seams	94
Average length of stylolites	0.44 inches
Average distance separating stylolite seams	3.0 inches
Approximate minimum loss by solution	41.0 inches
Minimum original thickness	325.0 inches
Percentage of approximate minimum loss	12.6 per cent

In the next case measurements were made involving additional criteria, such as those illustrated by Figures 4, 5, and 6. The calculations were again made on the Carthage, Missouri, marble. The following are the results:

Amount of stone measured	466.0 inches
Estimate of minimum loss by solution	135.0 inches
Minimum original thickness	601.0 inches
Percentage of approximate minimum loss	22.4 per cent

In a third instance measurements were made on highly stylolitic slabs of Tennessee marble (Holston formation). All criteria in evidence for determining the amount of rock loss were used. The following calculations resulted:

Amount of stone measured	144.0 inches
Number of prominent stylolite seams	98
Estimate of minimum loss by solution	74.0 inches
Minimum original thickness	218.0 inches
Percentage of approximate minimum loss	34.0 per cent

The foregoing figures may be surprising, but when it is realized that the full amount of rock removal may have been even considerably more, without further criteria for measurement, the significance of the solution process in the dwindling of certain rocks commands attention. The figures given show percentages of only minimum possible loss testified by the evidence. Some horizons may have been thinned as much as 40 to 50 per cent. It must not be construed, however, that all soluble rocks evidence as great an amount of loss as the foregoing calculations reveal. Some show little effect; others, considerable.

Following measurements in quarries the writer feels safe in esti-

mating that at least 5 per cent of the Columbus limestone (Middle Devonian) of central Ohio has succumbed to removal by solution. A larger figure will probably apply to the Salem limestone (commercially known as the Bedford) of southern Indiana.

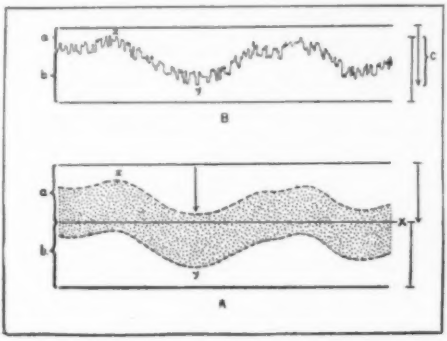

FIG. 4.—Diagram to illustrate an undulating stylolite seam and the necessary amount and distribution of solution to produce such.

B shows the nature of a common type of undulating seam, drawn from an actual specimen. The bed above, *a*, is fine-grained, light-gray marble. The rock below, *b*, is dark gray and coarser grained, bearing numerous fossils. The lithologic contrast between the two beds is distinct.

A shows the position of the beds before necessary solution took place. Solution started along *x*, a normal, smooth bedding plane. The dotted area shows the amount of rock which was removed to develop the seam of *B*. The dashed lines represent the approximate average boundaries of the solution zone. No attempt has been made to show the exact, jagged boundary. At *z* a greater amount of solution was in bed *a*, while at *y*, bed *b* succumbed to a greater amount of dissolving.

Although the actual length of the stylolites is but about ½ inch or less, the amount of solution which took place was fully four times as great. The minimum amount of thinning is shown by *c*.

The angle at which a quarry face or slab of stone has been cut relative to the direction of the stylolite parting will affect the apparent length of the columns and thus will affect calculations of actual amount of stone removed. At the same time the apparent thickness of the stone would be proportionately affected. Thus calculations of the percentage of rock loss would be correct. Most commonly quarry faces and stone slabs are cut approximately at right angles to the partings. Consequently the stone face is parallel with

the direction of the individual stylolites, and thus the length of the columns would serve as a true measure of the minimum possible loss through solution.

DEVELOPMENT OF CLAYLIKE RESIDUE

Inasmuch as no limestone, dolomite, or marble is composed of 100 per cent carbonates capable of being removed through the action of waters charged with CO_2, decomposition of such rocks by

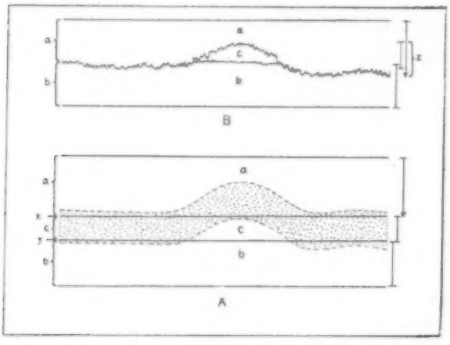

FIG. 5.—Diagram illustrating an undulating stylolite seam with a small remnant of a pre-existing bed lying adjacent to a pronounced upward curve in the suture.

B shows two distinct beds, *a* and *b*, in contact with one another at all places except at *c*, where a remnant of a pre-existing bed, of different lithologic character, exists separating them.

A shows conditions existing before solution occurred along the two bedding planes, *x* and *y*, which separated the three original beds from one another. The dotted zone is that of the material to be removed by solution in order to produce the effect illustrated in *B*. The minimum amount of thinning is indicated by *z*.

solutions leaves a claylike residue consisting of the less soluble constituents. The nature of such weathering is well known and will not be reviewed here. Such rock solution as is involved in the development of stylolitic and related phenomena must of necessity leave a residual concentration of the claylike materials which comes to rest as a cap at the ends of such columns as may be developed (see Fig 1). A small portion of this residue is strewn as a film along the sides of the penetrations, and thus slightly less than the total amount of residue is to be found resting as caps. (Where metamorphism of the

rock has occurred the residue is found in the altered condition.) The residue from this type of rock solution presents a twofold significance: (*a*) it introduces into the rock mass a concentration of insoluble substances which requires special interpretation; and (*b*) it offers another means of measurement of rock loss through solution.

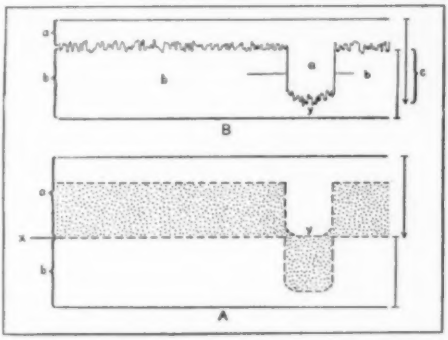

FIG. 6.—Diagram illustrating a striking but common situation testifying that the amount of rock removed by solution may be much greater than the length of the individual teeth of a stylolite seam might seem to indicate.

B shows an existing situation. Bed *a*, above the stylolite seam, is one shade of color, and bed *b* is a strikingly different shade and is different in texture. The portion of bed *a*, above *y*, is sharply set down in bed *b* to a depth of about $3\frac{1}{2}$ inches.

A shows the position and minimum possible thickness of the beds before the necessary solution took place. At *y* less of the overlying bed (perhaps practically none) and more of the underlying bed was removed than at any other place adjacent to the original solution plane, *x*. The dashed lines represent the approximate average boundaries of the solution zone. The dotted area indicates the rock to be removed by solution. The minimum amount of thinning is shown at *c*.

Interpretation of "clay partings."—It has been common practice to interpret all types of thin claylike partings in limestones, dolomites, and marbles as signifying simply a temporary change in conditions of sedimentation from those requisite for limestone-making to those necessary for clastic silt accumulation. This view has been often accepted in connection with the caps of stylolites, in which case an original continuous silt layer is considered as having been broken by the interpenetration of the columns. Evidence against this, in the case of stylolites, is abundant.

Most of the impurities scattered through limestones are nothing more than the clastic silts which have drifted out into the limestone-making waters. If the resulting rock is later subjected to decomposition by solution, the impurities become concentrated as a residue.

TABLE I*

ANALYSES OF SALEM LIMESTONE (BLUE) AND CLAYLIKE RESIDUE OF ASSOCIATED STYLOLITE SEAM, FROM QUARRY OF CONSOLIDATED STONE COMPANY, DARK HOLLOW DISTRICT, LAWRENCE COUNTY, INDIANA

CONSTITUENTS	I		II		III	IV	V
	Fresh Limestone		Residue		Percentage of Loss for Entire Rock	Percentage of Each Constituent Saved	Percentage of Each Constituent Lost
Silica (SiO_2)	0.84	.....	29.64	.....	0.10	88.30	11.70
Alumina (Al_2O_3)	0.18	.....	7.16	.....	0.00	100.00†	0.00
Ferric oxide (Fe_2O_3)	0.04	.....	8.22	.....	0.56	28.30	71.70
Ferrous oxide (FeO)	0.76	.....	0.84	.....			
Ferrous carbonate ($FeCO_3$)	.....	0.55	.....	.....	.....	.....	.....
Lime (CaO)	54.04	.....	14.80	.....	51.40	6.80	93.20
Calcium carbonate ($CaCO_3$)	.....	96.50	.....	.....	.....	.....	.....
Magnesia (MgO)	0.08	.....	0.44	.....	0.07	13.80	86.20
Magnesium carbonate ($MgCO_3$)	.....	0.17	.....	.....	.....	.....	.....
Potash (K_2O)	0.15	.....	3.58	.....	0.06	59.60	41.40
Soda (Na_2O)							
Total silicates and oxides not combined with CO_2	.....	1.63	.....	49.44	.....	.....	.....
Carbon dioxide (CO_2)	42.76	.....	12.10	.....	39.72	7.10	92.90
Volatile and combustible matter, less CO_2	0.60	0.60	19.14	19.14	0.12	79.80	20.20
Total	99.45	99.45	95.92	.....	91.50	.....	.....

* Column I, fresh Salem limestone (blue variety); Column II, black residue of stylolite seam associated with I. Analyses by Kenneth W. Ray, Indiana University. Columns III, IV, V, calculated by the writer.

† Alumina taken as constant.

It is such a residue that is formed when solution takes place within the rock along a crevice of any sort. The amount of residue which accumulates is dependent upon two main factors, namely, (*a*) the proportion of insoluble constituents in the original rock, and (*b*) the amount of rock which has been decomposed. Such residues are commonly black, dark gray, or brown in color, and show up vividly in the rock. In the case of small stylolite seams in marbles, for exam-

ple, the sharp outline of the structure is plainly brought out by the metamorphosed residual film.

The residue is not a true clay, or kaolin, since the chemical alterations necessary to convert a clastic silt sediment to kaolin are not completed in the initial decomposition of limestone. This would be especially true where the solution is within the beds and the minerals are not freely exposed to atmospheric gases. The residue is merely a concentration, with little chemical alteration, of the clastic fragments scattered throughout the limestone. Thus, chemically, such residual "clays" vary little from the expected composition of an ordinary shale. Such residual partings, however, lack the lamination produced by the sorting action of open waters.

The accompanying analyses (Table I) serve as an example to illustrate the chemical relationships existing between a limestone and the claylike residue of an associated stylolite seam. It is to be noted that the proportion of the insoluble substances, silica to alumina, is approximately the same in the limestone and in the solution residue. This is the expected relationship. Assuming the alumina to be least affected through chemical change and to remain constant, the silica shows the slight loss to be expected through possible desilication.

Many peculiar effects relative to the presence and distribution of claylike residues may be expected from solution within soluble rocks. In the case of well-developed stylolites, dark claylike films rest as caps at the ends (see Fig. 1). But if solution occurred only on one side of a crevice, such as a bedding plane, or if it occurred uniformly on both sides, no interpenetration of columns would result, and the insoluble constituents would be concentrated as a continuous thin claylike layer (see Figs. 3 and 7). In the case illustrated in Figure 3 the same parting at another place on the quarry wall showed ideal stylolitic development, proving solution to be the principal factor in its origin.

Many claylike residual seams, other than those associated with stylolites, may be expected in soluble rocks. Only when differential solution has taken place are stylolites formed; otherwise the stylolitic structure may be absent, leaving only the claylike residue as testimony to the solvent action. For example, the Maxville limestone, especially in Lawrence County, Ohio, is featured by numerous wavy

"mud-seams" from 1 to 6 inches apart throughout a thickness of 70 to 110 feet of rock. The stone is dense and semilithographic. The seams are undulating but are roughly horizontal, although some follow an inclined direction for various distances. The courses which they follow resemble considerably those of the small stylolite seams of the Tennessee marble. Such "mud-seams" are residues of limestone which has succumbed to solution within the bed rock mass.

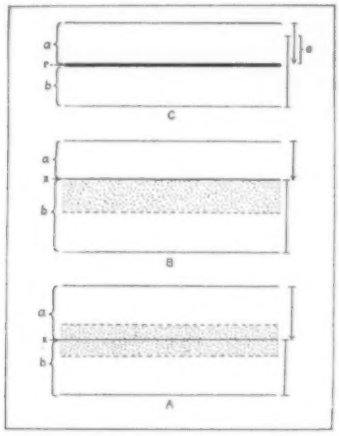

FIG. 7.—Diagram to illustrate how a smooth residual parting may be developed by uniform solution along a bedding plane.

C shows a black, claylike parting, *r*, between limestone beds, *a* and *b*. In *B* solution took place evenly below the bedding plane *x*. In *A*, uniform solution occurred both above and below the bedding plane. The dotted zone represents the rock to be removed by solution. The amount of thinning is indicated by *e*.

They are not, therefore, films of sediment laid down as silts under special, quickly changing conditions.

The Monroe dolomite of Ohio is beautifully laminated at certain horizons. Many of the laminae are black and quite vivid. They are often referred to as thin films of "carbonaceous material." Close examination under the lens shows many of them to be minutely stylolitic, suggesting, therefore, that solution has been involved. Might not such films be a solution residue, and thus the lamination of the stone emphasized? Similar examples are numerous. Solution,

leaving its peculiar residue of insoluble materials, may explain many peculiar claylike seams and films often found with various angular relationships to the normal bedding planes in carbonate rocks.

Solution residue as a measure of rock loss.—If the quantity of residual substance is measured and the approximate analysis of the rock from which it was derived is determined, data are sufficient to calculate the amount of original rock necessary to produce the residue. Consider, for example, the analysis of limestone in Column I of the foregoing Table I. In this case 96.5 per cent by weight is $CaCO_3$, leaving about 3.5 per cent of "impurities" to produce the essential mass of the residue. Converting these figures to percentage by volume, by considering the average specific gravity of limestone as 2.70 and of shale as 2.50, the proportion of $CaCO_3$ to impurities is approximately 96.7 per cent to 3.3 per cent. In this case, therefore, a stylolite of 10 inches in length, indicating solution of at least 10 inches of stone, should have a residual cap of approximately 0.33 inches. Compression resulting from superincumbent weight, as well as loss of a small portion of the residue by being strewn along the sides of the columns, would tend to reduce slightly the thickness of residue. Observations of stylolites bear out the relationships between length of the columns and thickness of the caps as outlined above.

In the case of a residual seam which is non-stylolitic, the quantity of claylike substance would serve as the only measure of the amount of rock removal. In the case illustrated in Figure 3, for example, the black seam is about three-eighths of an inch in thickness. The associated rock analyzed about 4.0 per cent insoluble matter. Solution of about 10 inches of stone would be required to leave a parting of such thickness.

CONCLUSIONS

Since solution within strata has reduced the thickness of certain rocks (especially limestones, dolomites, and marbles) by amounts perhaps as high as 40 per cent or more in some instances, the present thickness of the rock cannot be accepted as a true basis for determining the length of time required for its making. More time than the existing thickness would necessitate must, therefore, be allowed in the geologic history. The difference would be notable in the case of the Tennessee marble, for example. Imperfections in the strati-

graphic record, although not profound, must be recognized as a result of this peculiar type of rock destruction. An extensive "solution break" would present a missing leaf in the pages of rock history, as does a disconformity, carrying with it, however, a vastly different interpretation.

The development within the strata of claylike seams, or partings, by the decomposition of a portion of the original rock through solution requires an explanation very different from that usually attributed to the origin of such seams. They do not require sudden changes in the conditions of sedimentation, since their origin is secondary.

Many stratigraphic oddities, of which stylolites are the most pronounced, involve solution of the rocks in accounting for their origin.[1]

[1] The writer is especially indebted to Professor J. Ernest Carman, of the Department of Geology, Ohio State University, and to Mr. Wilbur Stout, of the Geological Survey of Ohio, for suggestions and assistance.

OUR PRESENT KNOWLEDGE OF THE PERMIAN OF THE GREAT PLAINS

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INTRODUCTION

For the past three decades geologists have been studying the Permian formations of the States of the Plains, particularly of Kansas, Oklahoma, and northern Texas, and the literature on the subject is becoming quite voluminous.[1] Until about two years ago, however, no geologist had ever succeeded in tracing any single Permian formation from Kansas across Oklahoma into Texas. Paleontologists, by the study of fossils, both vertebrate and invertebrate, had demonstrated the approximate equivalence of certain beds, but the men in the field had always gone astray in attempting to trace definite formations throughout the area occupied by the Permian in the three states.

This article has been prepared to discuss briefly three points, as follows: First, a statement of known facts regarding the Permian, which have been well recognized by geologists during the past twenty years; second, the results of studies accomplished during the past few years; and, third, certain unsolved problems as of this date.

[1] Only the most important publications are listed:

George I. Adams, "The Carboniferous and Permian Age of the Red Beds of Eastern Oklahoma from Stratigraphic Evidence," *Amer. Jour. Sci.*, 4th ser., Vol. XII (1901), pp. 383–86.

J. W. Beede, "Invertebrate Paleontology of the Upper Permian Red Beds of Oklahoma and the Panhandle of Texas," *Kans. State Uni. Sci. Bull.*, Vol. IV, No. 3 (March, 1907), pp. 113–71.

J. W. Beede, "Relationships of the Pennsylvanian and Permian Faunas of Kansas and Their Correlation with Similar Faunas of the Urals" (Abstract), *Science*, new ser., Vol. XXIX (April 16, 1901), 637–38.

J. W. Beede, "The Invertebrate Faunas and Correlation of Some So-called Permian Rocks of the Mississippi Valley, with Remarks on Their Stratigraphy" (Abstract), *Science*, new ser., Vol. XXIX (May 7, 1909), p. 752.

J. W. Beede "Formations of the Marion Stage of the Kansas Permian," *Kans. Acad. Sci., Trans.*, Vol. XXII (1909), pp. 248–56.

J. W. Beede, "The Bearing of the Stratigraphic History and Invertebrate Fossils

KNOWN FACTS

Practically all geologists who, during the past two decades, have studied the Permian of Kansas, Oklahoma, and northern Texas have recognized the following facts:

1. The Permian of the three states outcrops on the surface in a broad belt extending from northern Kansas, south across Kansas and Oklahoma, and as far as the Colorado River in Texas, a distance of about 600 miles. The average width of this outcrop is about 125 miles, and the total area occupied by the Permian rocks is approximately 75,000 square miles.

2. There are two general kinds of Permian rocks in this region, namely, red and non-red. The red Permian, usually called the red beds, consists of a great mass of red clay shales with certain ledges of sandstone, gypsum, salt, and dolomite. The non-red Permian consists chiefly of alternating beds of limestone and drab gray shale. Both the red and the non-red Permian are exposed in each of the three states.

3. The line of change of color between the red and the non-red sediments does not follow the strike of the rocks but, both in north-

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on the Age of the Anthracolithic Rocks of Kansas and Oklahoma," *Jour. Geol.*, Vol. XVII, No. 8 (1901), pp. 710–29.

J. W. Beede, "The Correlation of the Guadalupian and the Kansas Sections," *Amer. Jour. Sci.*, 4th ser., Vol. XXX (August, 1910), pp. 131–40; (Abstract), *Science*, new ser., Vol. XXXII (August 12, 1910), p. 224.

J. W. Beede, "Origin of the Sediments and Coloring Matter of the Red Beds of Oklahoma," *Science*, new ser., Vol. XXXV (March 1, 1912), pp. 348–50; (Abstract), *Science*, new ser., Vol. XXXV (February, 1912), p. 311; (Abstract) with Discussion by I. C. White, *Bull. Geol. Soc. Amer.*, Vol. XXIII, No. 4 (December 17, 1912), pp. 723–24.

J. W. Beede, "The Neva Limestone in Northern Oklahoma, with Remarks upon the Correlation of the Invertebrate Fossil Beds of the State. Eastern Outcrop of the Permian Red Beds in Oklahoma, with a Discussion of Lithologic and Color Changes," *Oklahoma Geol. Survey, Bull. 21* (December, 1914).

E. C. Case, "The Red Beds between Wichita Falls, Texas, and Las Vegas, New Mexico, in Relation to Their Vertebrate Fauna," *Jour. Geol.*, Vol. XII (1914), p. 243.

E. C. Case, "The Permo-Carboniferous Red Beds of North America and Their Vertebrate Fauna," *Carnegie Inst. of Wash. Pub. 207*, 1915.

E. C. Case, "The Environment of Vertebrate Life in the Late Paleozoic in North America; a Paleogeographic Study," *Carnegie Inst. of Wash. Pub. 283* (1919).

F. W. Cragin, "The Permian System in Kansas," Colorado College Studies, Vol. VI (March, 1896).

[Footnote continued on p. 417]

ern Texas and in the Kansas and Oklahoma region, presents a line diagonal to this strike, passing northwest-southeast in Kansas and northern Oklahoma, and southwest-northeast in northern Texas.

4. The base of the Permian, that is the line of Pennsylvanian-Permian contact, has not yet been definitely established, having been moved up and down the geologic column through several hundred feet of strata by various geologists and paleontologists during the past two decades, and is even today a matter of controversy. The United States Geological Survey places this line of contact at the base of the Cottonwood limestone of Kansas and northern Oklahoma, as also does the Kansas Geological Survey.

5. The general dip of the Permian formations in the eastern part of their outcrop in each of the three states is to the northwest, but on passing west this dip flattens out, and in western Oklahoma and the Panhandle of Texas the dip is to the east.

RESULTS OF RECENT STUDIES

During the past five years a number of men, largely petroleum geologists, working in different areas and engaged in studying the logs of wells throughout the general region, have arrived at certain rather definite conclusions regarding the Permian. Many of the re-

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F. W. Cragin, "Observations on the Cimarron Series," *Amer. Geologist*, Vol. XIX, No. 5 (May, 1897), pp. 351–63.

F. W. Cummins, *Second Annual Rept. Geol. Survey Texas* (1891), pp. 394–424.

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sults of the findings of these more or less independent investigators have been crystallized in a series of field conferences recently held, under the direction of the Oklahoma Geological Survey, in Oklahoma and adjacent areas in northern Texas and southern Kansas.

The more important of the results obtained in these field conferences may be summarized as follows:

1. The Anadarko Basin, a broad, structural trough, is recognized in the region north of the Wichita Mountains, southwestern Oklahoma. The reading in of this structural feature has probably done more than any other single thing to clarify the stratigraphy and correlation of the Permian in this region. Once this structural trough has been recognized, the various parts of the problem fall together like a puzzle picture, and that which has always been confusing and baffling at once becomes plain.[1]

2. The name "Greer" has been abandoned, and the name "Cloud Chief" is being used for the old "eastern area" of the "Greer," now known to be at a higher stratigraphic level than the formations of the "western area," which are considered to be "Blaine."

3. The Enid formation, which, as originally described, included all the Oklahoma Permian red beds below the base of the Blaine Gypsum,[2] has been subdivided into the following six formations, named in ascending order: the Stillwater formation, Wellington formation, Garber sandstone, Hennessey Shale, Duncan sandstone, and Chickasha formation.[3]

4. The Duncan sandstone of Oklahoma is recognized as the approximate stratigraphic equivalent of the San Angelo conglomerate of Texas and of the middle and upper portions of the Harper sandstones of Cragin, first described in Harper County, Kansas.[4] This being true, it will be understood that the San Angelo-Duncan-Harper horizon may be carried uninterruptedly from southern Kansas across Oklahoma, to the Colorado River in central Texas.

[1] Charles N. Gould, "New Classification of the Permian Red Beds of Southwestern Oklahoma," *Bull. Amer. Assoc. Pet. Geol.*, Vol. VIII, No. 3 (1924), p. 323.

[2] Charles N. Gould, "Geology and Water Resources of Oklahoma," *U. S. Geological Survey, Water-Supply Paper 148* (1905), p. 39.

[3] F. L. Aurin, H. G. Officer, and Charles N. Gould, "Subdivisions of the Enid Formation," forthcoming *Bull. Amer. Assoc. Pet. Geol.*

[4] F. W. Cragin, "The Permian System of Kansas," Colorado College Studies, Vol. VI (March, 1896), p. 18.

5. The horizon of the Blaine gypsum may now be traced uninterruptedly from southern Kansas south across west-central Oklahoma around the head of the Anadarko Basin, doubling back along the south side of this basin, around the west end of the Wichita Mountains, and thence south across Red River as far as San Angelo, Texas, an exposure on the surface of 600 miles. The Blaine may be considered the key bed for the correlation of the Permian of this region.[1]

6. The Whitehorse sandstone of Kansas and Oklahoma is found to be the stratigraphic equivalent of the Lake Trammel sandstone of Texas, and the horizon may be traced continuously in the three states.

7. The San Angelo sandstone is considered by Beede to be the base of the Double Mountain formation of Texas. Therefore, the following named formations in Oklahoma constitute the stratigraphic equivalent of the Double Mountain formation (group) of Texas, named in ascending order: Duncan, Chickasha, Blaine, Dog Creek, Whitehorse, Day Creek, Cloud Chief, and Quartermaster.

8. It has been shown that the Wichita-Clear Fork beds of Cummins, in Texas, are the stratigraphic equivalents of the "red beds of uncertain relations" described by the writer, in the region surrounding the Wichita Mountains and between these mountains and Red River, and the Texas names are now being used to apply to these rocks in this part of Oklahoma. It has not been found possible so far to divide the Wichita from the Clear Fork in Oklahoma. These beds are now known to represent the Stillwater, Wellington, Garber, and Hennessey of northern Oklahoma.

9. Studies chiefly by various petroleum geologists have demonstrated that the Permian red beds (Cimarron series of Cragin) underlie the Tertiary and Cretaceous rocks of central and western Kansas, extending westward from a line drawn diagonally across the state from Sumner County, northwest to Smith County; and it now appears very probable that these same Permian red beds may be traced still farther north and west to connect with formations outcropping in the Black Hills and along the Rocky Mountain front.

[1] Charles N. Gould, "The Correlation of the Permian of Kansas, Oklahoma and Northern Texas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. X, No. 2 (1926), pp. 144–55.

10. Partly by the work of geologists working independently, and partly as the result of the various field conferences, a series of peculiar phenomena have been brought to light. These are the so-called "channel" sandstones of the red beds. One of these sandstones in Grady County, Oklahoma, has been named the Verden sandstone.[1] Other similar "channels" are known to occur, one in Woods and Woodward counties, northern Oklahoma, and one in Collingsworth County in the Panhandle of Texas. These "channels" consist of a bed of conglomeratic, fossiliferous, and cross-bedded sandstone, usually 5–20 feet thick, and not more than half a mile wide, extending across the country in a practically straight line for a distance sometimes of 20 to 40 miles. They occur either near the top of the Dog Creek shales or in the Whitehorse sandstone. The origin of these "channels" is not known at this writing.

CERTAIN UNSOLVED PROBLEMS, AS OF MAY 1, 1926

In listing these problems as unsolved it is not intended to convey the impression that no work has been done on them. In point of fact many of these problems have engaged the attention of some of our most careful workers for many years. No one, however, would believe that the final word has been said on any one of these problems, for as additional data come to light new interpretations must constantly obtain.

1. The origin of the Permian sediments: whether these rocks came from the Arbuckle-Wichita range and its northwestern extension, from the buried Amarillo Mountains, from the Ancestral Rockies, or from the Ozarks. When this problem has been definitely solved many related problems will be easy.

2. The origin of the red color of the red beds.

3. The Pennsylvanian-Permian contact.

4. The Wichita-Clear Fork line of contact in the region around the Wichita Mountains and between these mountains and Red River in southern Oklahoma.

5. The origin and extent of the Anadarko Basin.

[1] R. D. Reed and N. Meland, "The Verden Sandstone of Oklahoma," *Journal of Geology*, Vol. XXXII (1924), pp. 150–67.

6. The origin and classification of the various "channel" sandstones.

7. The origin of the salt, anhydrite, gypsum, and dolomite beds, and a classification of the dolomite beds.

8. The "pseudo anticlines" of the Quartermaster and other upper Permian beds of western Oklahoma and northwestern Texas.

9. The correlation of the Alibates dolomite, Pack Saddle gypsum, and other beds in the Amarillo region of the Panhandle of Texas with known formations in western Oklahoma.

10. The relation of the Big Basin sandstone and Hackberry shales of Clark County, Kansas, to the Cloud Chief and Quartermaster formations of western Oklahoma.

CONCERNING INCLUSIONS IN IGNEOUS MAGMAS

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ABSTRACT

Field occurrences are described which indicate that there has been a profound reaction, in the cases cited, between granite magma and some large inclusions in the magma resulting in the advancement of the crystallization of a part of the magma to pegmatite. The occurrences are regarded as illustrative of some of Bowen's views of magmatic reaction.

Bowen[1] has made an elaborate experimental study of the reactions which take place between molten magma and included foreign rock fragments which the magma may contain. He has shown that not only are fragments of rock included in molten magma profoundly altered by the magma, but also that these included fragments, in undergoing change due to their contact with magma, exert an influence on the magma itself, actually affecting the nature of its crystallization. Ordinarily the extent of this influence in natural magmas is obscure or is, for a given mass of inclusions, small on account of the size of the magma. The occurrences cited here are believed to be such that the extent of the mutual influence can be fairly recognized. They are thought to represent magma which, after having been virtually separated from a larger body while in the molten state, came into intimate contact with a relatively large mass of inclusions and was materially affected by them. The apparent influence of the inclusions on the separated molten magma is quite marked. This paper, then, offers field evidence of a unique sort in support of the conclusions drawn by Bowen in the laboratory.

Bowen has classified some of the more common minerals of igneous rocks into what he has termed a "reaction series." This series represents the course of alteration or change which mineral species may follow during the normal differentiation of a magma, or which rock fragments included in more "acid" magma may follow.

[1] N. L. Bowen, "Behavior of Inclusions in Igneous Magmas," *Journal of Geology*, Vol. XXX (1922), p. 513.

In general the change is from the more mafic minerals to the more felsic. Magma cannot dissolve minerals of included rock fragments which are higher in the reaction series than those minerals with which the magma is saturated, but it can attack and make over the more basic minerals into those with which it is saturated. To do this, material is added from the magma, but in a very definite way. By following in its normal course of crystallization the magma is enabled to yield to the inclusion the material required, this being brought about by the reactions of the minerals separating in a magma with the still liquid portion of the magma. As a corollary, then, the inclusions may be said to force the magma along in its natural course of crystallization.

It is obvious that a large mass of molten magma is capable of making over considerable amounts of included material before it will show very much change attributable specifically to the influence of these inclusions. And especially is this true since the influence of inclusions is not ordinarily well localized. But if a part of a magma should become separated from the main body and become also intimately associated with wall rock and included fragments, then the conditions are favorable for any reactions which may be possible between the molten and solid rock. Probably the most convincing indication that there has been a reaction is the advancement of differentiation (for instance, the presence of pegmatite) in that part of the magma which contains inclusions. The following descriptions are of field occurrences[1] which show these characteristics.

In the Bruce Mines Map Area,[2] Ontario, in Morin Township, Con. II, Lots 9 and 10, there is, in a large area of pre-Huronian granite, a small area (slightly over a half-mile in diameter) containing inclusions. From the center of the small area where the inclusions are quite crowded they become fewer per unit area outward, grading into uninterrupted granite. The main granite body locally appears to be slightly low in quartz. The granite filling between the inclusions contains a very large amount of granite pegmatite, not in sharply defined dikes, but irregularly distributed through it, and

[1] The field work was done while engaged in geologic explorations for the Geological Survey of Canada.

[2] Map to accompany Memoir 143, by W. H. Collins, Geological Survey of Canada.

with margins grading into normal granite. The percentage of pegmatite in the granite between the inclusions increases toward the center of the area of inclusions, and in places pegmatite is present to the exclusion of granite. The pegmatite is typically feldspar and quartz with small amounts of hornblende and mica; the texture of the pegmatite does not appear to differ at all from that of the granite pegmatite not associated with inclusions. The inclusions themselves are of schist, consisting of biotite, dark hornblende, and a light-colored feldspar, all rather fine grained. All the inclusions seen are of practically the same mineral composition and texture; they do not show any noticeable change from margin to center of the individual inclusion. The granite, remote from inclusions, contains a small amount of pegmatite only. There is, then, a very pronounced change in the pegmatite content of the granite from the inclusion-free part to that part which is between the inclusions, that is, from the margin of the inclusion-crowded area to the center of it. Normal granite, without inclusions, passes by gradation into granite and pegmatite with inclusions, and, further, into pegmatite with a small amount of pegmatoid granite carrying an abundance of inclusions.

On Stoney Lake, in Timber Berth 195, Ontario, near the east end, is another well-exposed occurrence that is entirely similar to the last in general relations. The area is one of granite in which is a mass of inclusions covering an area about one-quarter mile square. The granite near the inclusions is again the normal pre-Huronian type, moderately coarse, quite fresh, and cut by a few dikes of pegmatite and aplite. The inclusions are almost entirely very coarse hornblende, but they contain also a small amount of red feldspar. They are quite close together and so arranged as to appear to be the fractured remnants of a once larger inclusion. The inclusions are uniform in appearance, as in the occurrence in Morin Township, but much coarser, and contain a smaller variety of minerals. The filling between the included fragments is in small part pegmatoid granite, but is mainly granite pegmatite, quite coarse (1 to 3 inches), and much of it shows graphic structure. This is true of all the filling seen, both narrow and wide apophyses. Here, too, the granite around the area of inclusions contains little pegmatite, but the filling between the inclusions is high in pegmatite.

In Jarvis Township, near Sault Ste Marie, Ontario, in the vicinity of the Victoria silver-head mine, especially good examples were studied. Very coarse hornblendic inclusions of large size—one-quarter to one-half mile in extent—occur in, and are surrounded by, pre-Huronian granite and are cut by persistent dikes of pegmatitic and aplitic granite. The inclusions appear to have been only partly broken up by the influence of the granite, and in this respect differ from the two previously mentioned occurrences, but the relationships are otherwise essentially the same. That is, granite which contains included fragments gives place between the fragments to granite and pegmatite granite, in intimate intermixture and not sharply defined from one another.

To sum up the relationships which these examples bring out: an igneous rock of well-known type contains foreign matter in the form of angular and subangular inclusions. The inclusions do not show the extent to which they have undergone alteration attributable to the igneous rock other than fracturing. But the igneous rock between the inclusions is very noticeably different from the rock not so intimately associated with the inclusions. The most obvious difference is in the degree of differentiation which the two rocks have reached, that occurring in intimate association with the inclusions having reached the pegmatite stage, and therefore being differentiated further than the rock not directly in contact with the inclusions.

Other examples might be cited, but these three serve to illustrate abundantly the principles involved, and are mentioned because of the exceptionally good exposures and because special attention was directed to their study. Illustrations are too numerous to explain the association of pegmatite and inclusions as a coincidence, the inclusions merely occurring in a pegmatite area of the granite. The inclusions described are all high in ferromagnesion minerals; this seems to be generally the most favorable type of inclusion for the development of a granite-pegmatite association. All the inclusions are in pre-Huronian granite of the normal kind so abundantly described in the literature, and all are fractured or shattered and filled by granitic material which is largely or entirely pegmatite and aplite. Other inclusions which are less mafic have been studied

in the same localities for similar relationships, but association with pegmatite in the manner described is either less obvious or absent. This is true not merely as a result of more extensive metamorphism of the less-mafic inclusions, for if this were so it would be expected that the margins of such inclusions would not be sharp, but many are. In the experience of the writer it does appear to be true that mafic inclusions in granite show association with pegmatite especially well.

It does not seem possible to attribute these associations of angular mafic inclusions with pegmatite to one cause alone, but it does seem reasonable to lay stress mainly on two influences. The first of these is mechanical; the second, chemical. If we assume a large xenolith to be suspended in a molten magma and to be subjected to stresses which have their origin in the magma, such as the heating of the inclusion and differential stresses resulting from movement within the magma, then normally the xenolith will be shattered first into larger blocks and these subdivided until the whole is frozen. During this process molten magma is forced or drawn into the spaces between the fragments of the xenolith and there is reaction along the contacts between the included and including rock. There are then two factors which work together to give rise to the association of the included material and pegmatite of the including rock. First, the molten magma forced or drawn into the interstitial spaces of the inclusion would be the more mobile part of the magma, and this is likely to be that from which pegmatite will later crystallize. But if this factor were the only one operative, then all kinds of inclusions so shattered should show a similar association in some noticeable degree; but, as pointed out above, this is not always true. The second factor, and that which is regarded as most important in the formation of the pegmatite, is the reaction which takes place between the two rocks. In the experiments of Bowen (described in the paper referred to) he brings out certain principles which seem to be supported strongly by these field observations. Some of those which are directly applicable have been mentioned briefly above, namely, that the reactions which take place between "acid" magma and "basic" inclusions result in the making-over of the inclusions

while the magma is forced along in its natural course of crystallization.

It is believed that these principles serve to explain in large part the associations described. Granitic liquid (and crystals) penetrated the inclusions and was essentially cut off from the main magma, but came even more intimately into contact with the mafic inclusions than before. Here there was reaction due to the mutual influence of the inclusions and the magma and both doubtless were considerably changed. Differentiation proceeded to the pegmatite stage in the isolated granitic liquid, but elsewhere it has not proceeded so far. Although it is impossible to say to what extent inclusions were altered, yet it is possible to estimate the additional differentiation which took place in the magmatic liquid, cut off from the remainder of the magma and in contact with inclusions. The estimate is based on a study of the neighboring granite itself, which indicates roughly the degree of differentiation of the granitic liquid at the time of injection into the inclusions. The additional differentiation is attributed largely to the reaction of the granitic liquid with the inclusions. On the margins of the inclusion-filled area diffusion and convection would tend to counteract the concentration of pegmatite, but within the inclusions, pegmatite formed would remain.

The inclusions are not regarded as segregations. The area of inclusions is an area of fragments showing a gradation in number or concentration from the center outward. The most convincing evidence is the sharp angularity of many of the fragments and the commonly sharp boundary lines between fragment and including rock. The wall or roof of the batholith from which the inclusions were derived is in each case comparatively near at hand. But even if the inclusions were regarded as early segregations later broken up and attacked by the leucocratic differentiate, the argument outlined is in no way affected.

The point which it is desired to emphasize, then, is that the field observations described indicate that reactions of the sort discussed by Bowen are operative on a considerable scale and can be recognized under favorable conditions as having been operative in the evolution of rock types. In the nature of the case the process

tends to hide traces of itself, and it is only under conditions such as those described that natural illustrations may be found.

Of theoretical interest is the added emphasis which these facts place on this mode of origin of pegmatite. But the writer has found of considerable practical value the observation that inclusions in close association with pegmatite in the manner described are a common occurrence near contacts, doubtless because it is here mainly that shattering of the inclusions takes place, and if chilling follows soon, then the counteracting influences, such as diffusion and convection, are not so able to obscure the results as would be true if the inclusions were able to leave the contact zone.

EXPERIMENTS ON THE DEHYDRATION OF GYPSUM

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ABSTRACT

Experiments using heat, heat and pressure, and pressure alone show that heat is most effective in dehydrating gypsum.

The primary deposition of both anhydrite and gypsum in nature has been established by many geologic observers[1] and verified by the physical-chemical work of Van't Hoff and his associates.[2] It is also well established that natural transformations from anhydrite to gypsum are not uncommon,[3] but whether this is a reversible reaction in nature is still uncertain. Newland[4] has emphasized the fact that in New York State, bedded gypsum deposits commonly pass gradually, at depths of a few hundred feet, into deposits that are mostly anhydrite. The question is whether, in such instances, the bed as originally laid down was gypsum or anhydrite. Has the pressure of overlying sediments induced a dehydration of gypsum to form anhydrite; or has pressure, combined perhaps with less active ground-water circulation, inhibited the hydration of anhydrite (with accompanying large increase in volume) to form gypsum?

Newland[5] is inclined to think that natural dehydration of gypsum may take place. The following experiments are offered as a contribution to this problem. They show that at ordinary tempera-

[1] F. W. Clarke, "Data of Geochemistry," 5th ed., *U.S. Geol. Survey. Bull. 770*, p. 586; J. D. Dana, *Manual of Geology*, 4th ed., p. 554; D. H. Newland and H. Leighton, "Gypsum Deposits of New York," *N.Y. State Museum Bull. 143* (1910); R. W. Stone, "Gypsum Deposits of the United States," *U. S. Geol. Survey. Bull. 697* (1920); D. H. Newland, *Mineral Industry*, Vol. XXVIII (1920), p. 333; A. F. Rogers, "Notes on the Occurrence of Anhydrite in the United States," *School of Mines Quarterly*. Columbia Univ., Vol. XXXVI, pp. 120 ff.

[2] Van't Hoff and Weigart, *Sitzungsber. k. Akad. Wiss.*, Berlin (1901), p. 140.

[3] D. H. Newland, "Relation of Gypsum Supplies to Mining," *Trans. Amer. Inst. Min. and Met. Eng.*, Vol. LXVI (1922), p. 91.

[4] *Ibid.*, p. 93. [5] *Ibid.*, p. 93.

tures and within the brief periods of the experiments, one half hour to five days, pressures of from 600 to 316,000 pounds per square inch, corresponding to the pressure exerted by 512 to 268,800 feet of limestone, produced no dehydration of gypsum. It is recognized as possible that similar pressures, maintained through long periods of time, may produce dehydration. During the course of the experimental work a paper by Oliver Bowles and Marie Farnsworth[1] appeared, which contains an excellent theoretical discussion of the problem but no conclusive experimental evidence. The writer, therefore, feels justified in offering the evidence presented by his experiments.

EFFECTS OF PRESSURE

For pressure tests a piece of gypsum from the University of Chicago collections was used. This was ground and a sample taken for analysis; a sample was also taken before grinding to compare with the ground material, to make sure that no alteration took place during the grinding. The grinding was done in order to facilitate the charging of the material in the mold and to facilitate sampling. It was found that a block cut to fit the mold shattered with very little pressure and behaved, from then on, as the crushed material did. An analysis of the crushed and uncrushed material follows:

	Ungrounḍ	Ground
$CaSO_4 . 2H_2O$	97.37	97.36
$CaCO_3$	1.29	1.29
Al_2O_3 and Fe_2O_3	0.28	0.30
Insoluble	0.20	0.21
Moisture*	0.75	0.75
MgO (not determined)	.....	.....
Total	99.89	99.91

* Drying the sample at 100° C. or 105° C. for three hours did not give constant results, and no other heat methods were found which would, so the drying was done by leaving the sample in a dessicator over concentrated sulphuric acid for five days.

For the pressure tests the crushed gypsum was put in a split mold provided with an accurately fitting plunger. The mold had a hole, three millimeters in diameter, drilled through it in the side near the bottom to permit any water liberated to escape, and so that reac-

[1] Oliver Bowles and Marie Farnsworth, "Physical Chemistry of the Calcium Sulphates, and Gypsum Reserves," *Economic Geology*, Vol. XX (1925), pp. 738–45.

tions, if any took place, might not be in a sealed system. This hole also served to obtain a differential pressure instead of direct compression. The mold containing the desired quantity of gypsum, usually about fifty grams, was placed in the press, the plunger inserted, and pressure applied. The press used was a vertical hydraulic with a six-inch ram capable of developing 6,000 pounds per square inch, or, on a one-inch plunger, capable of producing 316,000 pounds. When the desired pressure was obtained, the press was locked and this pressure held constant for as long as desired. The time periods used were one half-hour, one hour, three hours, and five days, except with pressures over 100,000 pounds per square inch. One attempt was made to hold 316,000 pounds for a longer time than three hours, but after somewhat less than four hours it was found that the bolts locking the mold together were stretching and that the mold had warped.

The pressures used were 600, 1,000, 1,500, 3,000, 6,000, 26,000, 54,000, 108,000, and 316,000 pounds per square inch. At 36,000 pounds per square inch gypsum was very slowly extruded from the mold. Analysis of the material which remained in the mold, after the pressure had been applied, and of the extruded material (the analyses of these were the same), failed to reveal any loss of water of hydration. The slight differences noted can easily be accounted for by the loss of mechanically held moisture. Analyses which show the greatest loss of moisture follow:

	No. 1	No. 2	No. 3	No. 4
$CaSO_4.2H_2O$	97.36	97.36	97.35	97.36
$CaCO_3$	1.29	1.29	1.29	1.29
Al_2O_3 and Fe_2O_3	0.30	0.30	0.30	0.30
Insoluble	0.21	0.21	0.21	0.21
Moisture	0.71	0.73	0.67	0.70

No. 1 was pressed at 6,000 pounds for five days; No. 2 was pressed at 36,000 pounds for five days; No. 3 was pressed at 108,000 pounds for three hours: No. 4 was pressed at 316,000 pounds for more than three hours—until the mold was sprung.

EFFECTS OF HEAT AND PRESSURE

For these tests a quantity of gypsum was purchased from the Central Scientific Company, and this material was ground and

sampled as in the tests with pressure alone. Analysis of the ground material is as follows:

$CaSO_4.2H_2O$	98.16
$CaCO_3$	0.48
Al_2O_3 and Fe_2O_3	0.21
Insoluble	0.25
Moisture	0.87
MgO (not determined)	.....
Total	99.97
Water of hydration (determined)	18.81
Water of hydration (calculated)	19.03

Samples of this material were subjected to 600 and 1,000 pounds pressure at 50° C., 100° C., and 150° C. for half an hour. This work was done in flat-plate commercial presses heated by superheated steam.

The total amount of water which might be present in the sample is the theoretical water of hydration, 19.02 per cent plus the mechanically retained moisture, 0.87 per cent—a total of 19.89 per cent.

The amount of water remaining in the samples after the application of heat and pressure is shown in percentage in Table I.

TABLE I

Temperature	Pressure of 600 lbs. per sq. in. (Per Cent)	Pressure of 1,000 lbs. per sq. in. (Per Cent)
50° C.	19.75	19.85
100° C.	19.75	19.69
150° C.	6.69	6.09

These results show very slight dehydration below 150° C., but at 150° C. a notable amount of dehydration occurs. The indication is that dehydration is not so much a matter of pressure as of temperature.

EFFECT OF HEAT

To check the effect of heat against the foregoing heat and pressure experiments, a sample was heated for half an hour at 150° C. under atmospheric pressure, and was found to have 6.74 per cent

water remaining; very little more than in the material heated under a pressure of 1,000 pounds per square inch. It was also found that material dried at 105° C. and at 120° C., under atmospheric pressure, did not come to a constant weight, even when heated for five days; while, if the temperature was raised to 150° C., complete dehydration —a loss of 19.18 per cent moisture—took place in this time. Apparently 150° C. is, or is very near, the critical temperature of gypsum.

CONCLUSIONS

From the foregoing evidence I conclude that temperature is vastly more important than pressure in the dehydration of gypsum. Pressure may accelerate the dehydration, but pressure alone seems incompetent to accomplish dehydration. There is no evidence of dehydration with a differential pressure of 316,000 pounds per square inch at 20° C.; while at one atmosphere pressure and 150° C., there is practically complete dehydration. The time factor is one variable which can not be readily evaluated from such experiments, and it is possible that time in the geologic sense, with pressure, is more of a factor than these experiments indicate. Of this, however, there is no positive evidence.

Acknowledgment must be made for the valuable assistance of Professor H. McCormack of Armour Institute with the chemical analyses; to the Armour Institute of Technology for the use of a hydraulic press and laboratory facilities; and to the Brunswick-Balke-Collender Company for the use of a heated commercial press. The writer is also indebted to Dr. E. S. Bastin of the University of Chicago for suggesting the problem, for suggestions during the work, and for criticism of the manuscript.

FORMATIONS OF THE NORTH SHENSI BASIN, CHINA

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ABSTRACT

The North Shensi Basin, embracing the southern Ordos, northern Shensi, western Shansi, and eastern Kansu, previously unvisited and unmapped by geologists, was found to contain upward of 20,000 feet of sediments varying from Cambro-Ordovician to Recent in age, including the mantle of 1,500 feet or more of loess. About twenty formations or phases were differentiated, of which three are Cambro-Ordovician, one Carboniferous (Pennsylvanian ?), one Permian, one Permo-Triassic, ten Jurassic, one Cretaceous, one Tertiary, the Tertiary-Pleistocene loess, and miscellaneous Recent deposits. The Carboniferous and older beds are predominantly marine; the younger beds are largely continental. The basin is surrounded by a ring of horsts and grabens involving chiefly Carboniferous and Cambro-Ordovician beds. Dips are toward the center of the basin, except on the west, where the beds probably abut against a great fault.

INTRODUCTION

In 1913–15 the writers made certain economic explorations in China for American clients, the major part being in the North Shensi Basin, comprising western Shansi, northern Shensi, and eastern Kansu (Fig. 1). The work was conducted under great pressure owing to time limitations, over 100,000 square miles being covered in a reconnaissance way by ourselves and our associates, including Frank A. Herald, V. H. Barnett, E. L. Estabrook, Ernest Marquardt, and John M. Lovejoy, within a period of nine months. The region lies west of the areas covered by Richthofen and Willis and Blackwelder in Shansi and north of that of the same geologists in central and south Shensi. So far as known, no geologist had previously entered the territory.

The field work continued almost up to the last minute before our return to the United States and, the aims of the explorations having been accomplished, no provision was made for the digestion of the large amount of field data or the preparation of reports beyond those pertaining to the economic objects of the work. On leaving, all note books pertaining to Shensi and Kansu were left with our clients.

When the economic work was eventually abandoned a year or

two later, the various field reports and certain preliminary maps and sections were presented to the Chinese government, which had shared with our clients the expense of the explorations, although we ourselves were employed by and responsible only to the latter. In relinquishing the notebooks and other material we had in mind their possible misinterpretation by others, and therefore specifically stated that "they represent field impressions only and not final conclusions and we will not be responsible for any deductions drawn therefrom by others."

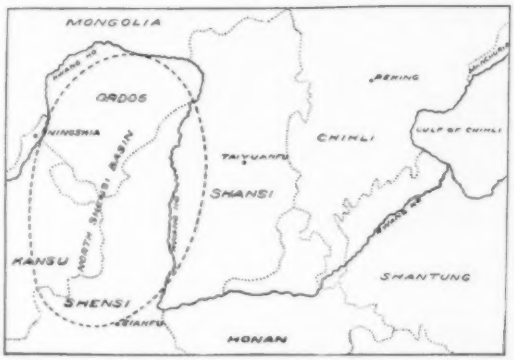

FIG. 1.—Sketch map of North China, showing location of the North Shensi Basin.

For business reasons, the results of our explorations were treated as confidential for several years. Permission to publish was later granted, but the pressure of other work has until recently prevented the working up of the material by us. In the meantime certain members of the Geological Survey of China, to which our geological material had been turned over upon its organization, published some of the matter as their own,[1] and elsewhere[2] quoted in whole or in part a geologic column which was intended by us for temporary field purposes only and did not at all represent our final conclusions.

That the use of the data mentioned was inadvertent, as explained

[1] T. O. Chu, "The Oil Fields of China," *Bull. Amer. Assoc. Pet. Geol.*, Vol. VIII (March-April, 1924), pp. 169–77; *ibid.*, Vol. IX (December, 1925), pp. 1295–98.

[2] C. C. Wang, "On the Stratigraphy of North Shansi," *Bull. Geol. Society of China*, Vol. IV, Part I (1925), pp. 57–67.

by Mr. Chu in his later communication, is cordially acknowledged. It seems best, however, before being further quoted, to put on record the actual succession worked out by us for the North Shensi Basin on the basis of field work and subsequent office studies. In the matter of age determinations we gratefully acknowledge our indebtedness to the Geological Survey of China. There was no paleontologist among our associates, a fact greatly to be regretted from the scientific standpoint, although in no way affecting the economic objects of the explorations. We would point out, however, that in our original application of the term Carboniferous, we followed the usage of the United States Geological Survey in including the Permian under this head, and did not limit the word to the time equivalent of the Pennsylvanian (and Mississippian?) as the Chinese Survey appears to do.

In the great area covered, considerable tracts are necessarily unvisited, and in the absence of original notes much dependence has been placed on field maps compiled from notes by draftsmen largely after our return to America and hence without revision. Moreover, there is always a certain likelihood of omissions and errors arising from the utilization of the work of associates, even when the original work is carefully done.

Basis of units used.—In an area of the size of the North Shensi Basin it is necessary, at least in the early and preliminary stages of mapping, to use broad and inclusive units based on similarity of lithologic character rather than individual beds which in general are of very limited extent and of no particular significance. We have followed this principle in the area under consideration. The units are really series, but because of the use of this term by the United States Geological Survey and others in a specific rather than a general sense, we have adopted the word formation instead, using it in the same sense as the last-mentioned bureau. Each formation will logically be broken up, as detailed knowledge of the region becomes available, into lenses or members, or into subdivisions based on paleontology.

Geological succession.—The succession of the beds in the Shensi Basin may be presented most concisely by means of a geological column such as that given below. The formation names are geographical, being taken from provinces, cities, or rivers in or near

which the beds are typically exposed. Full descriptions will be published in a detailed paper on the geology of Shensi.[1]

GEOLOGICAL COLUMN

			Max. thickness (feet)
Recent	Recent loess, stream alluvium, dunes and gravels on old loess, etc.		several hundred
	UNCONFORMITY		
Pleistocene	Main loess body (Huang-tu formation) with internal unconformities		1,500
Tertiary	Basal sandy loess, etc. (Huang-tu formation)		500
	Local sub-loess gravels, etc.		1,000
	UNCONFORMITY		
Cretaceous (Late)	Lung-chow formation. Sub-loess gravels, sands, and clays		1,000+
	UNCONFORMITY (Peneplanation)		
Jurassic	Tien-chi formation (Gypsiferous beds)		(?)
	Hwan-ho formation (3,000± ft.) — Hwan-hsien phase	Bright greenish shales and sandstones (no red)	600
	Hwan-ho formation (3,000± ft.) — King-yang phase	Alternating green and red sandstones and shales	1,800–2,500
	Hwan-ho formation (3,000± ft.) — Tan-pa-li phase	Red sandstone and shale (little green)	0–600
	Hwa-chi sandstone	Regularly bedded red sandstone with little shale	1,000
	Lo-ho sandstone	Massive false bedded red sandstone	2,000
	An-ting limestone	Limestone and red shale (northern equivalent of I-chun) (200 ft.)	200–500
	I-chun conglomerate	Conglomerate, etc. (southern equivalent of An-ting) (500 ft.)	
	Disconformity		
	Shen-si formation (6,000–7,000 ft.) — Tien-tou phase	Massive gray to pink sandstones with some shale	800–1,500
	Shen-si formation (6,000–7,000 ft.) — Yen-an-fu phase	Coal measures with massive sandstone at top and bottom	1,000
	Shen-si formation (6,000–7,000 ft.) — Yen-chang phase	Dense, hard, thin-bedded gray sandstones	4,000

[1] To be submitted for publication in *Bulletin of Geological Society of America*.

GEOLOGICAL COLUMN—*Continued*

			Max. thickness (feet)
Permo-Triassic	Pu-hsien formation	Sandstone and red shale	*2,000
Permo-Carboniferous	Shan-si formation	Upper coal measures (Permian)	600
		Disconformity	
		Lower coal measures (Lower and middle Carboniferous)	400
UNCONFORMITY			
Cambro-Ordovician	Ki-chou limestone	Massive gray limestone	5,000
	Tung-chuan quartzite and San-Yuen freestone	Both include a little red shale and represent respectively eastern and western phases	500
UNCONFORMITY			
Algonkian	Schists, etc. with internal unconformities		
UNCONFORMITY			
Archean	Gneisses, schists, intrusive granites, etc.		

*There is a possibility that the thickness of the Pu-hsien is underestimated. Accurate determinations are difficult because of folding and faulting.

The investigation of the Archean and Algonkian was outside the province of our work. The subdivisions and their relations have been discussed in detail by Willis and Blackwelder.[1] The Tung-chuan quartzite and San-yuen freestone are probably respectively the west Shansi and central Shensi equivalents of the Man-to shales of east Shansi. Our use of the name Ki-chou corresponds with theirs.

The term Shan-si, which was originally applied by Willis and Blackwelder to what they regarded as Carboniferous beds, has been transferred by the China Geological Survey to the upper portion of the coal measures, which are of Permian age, while the name Tai-yuan was applied to the lower or Carboniferous division and the term Yueh-men-kou to the formation as a whole. We see no reason for substituting the new for the older name of identical beds, hence adhere to the use of Shan-si in its original sense. A new name, if necessary, should be given to the newly separated paleontological division. From the mapping standpoint the Shan-si formation as a whole is the only convenient unit, there being no marked difference in character to warrant lithologic separation. The China Survey has

[1] *Research in China*, Carnegie Inst. of Wash., 3 vols. and atlas, Publication 54, 1907.

also given names to many of the individual beds, but these are of local interest only.

The name Pu-hsien is applied to the red beds originally called Fen Ho by us, the latter term being abandoned because of its prior use as the name of a physiographic stage by Willis and Blackwelder. Fön Ho and Fönn Ho are other spellings of the same term.

The Jurassic formation names are all new, and are applied to the subdivisions of the North Shensi Basin as worked out by us. The thicknesses are based on deep well records and careful determinations of dip by transit, plane-table alidade, and levels. They are believed to be conservative.

The Hwan-ho formation has been retained in the Jurassic rather than included in the Cretaceous, as has been done by the Geological Survey of China, for the reason that it is fully consolidated, follows the known Jurassic beds without interruption, and was tilted with the latter and beveled by the Cretaceous peneplanation. Where the Cretaceous has been definitely identified in the adjoining regions in Mongolia the deposition is found to follow, not precede, this peneplanation.[1] The same is true of the thick, mainly unconsolidated, white to orange gravels, sands, and clays of the Lung-chow formation in the vicinity of Lung-chow and Kien-yang (Chien-yang) in western Shensi (Lat. 34°45′ N., Long. 107° E.), which here rest on beveled coal measures of probable Carboniferous or Permo- Carboniferous age. Fossil fish obtained by the China Survey seem to point to the Cretaceous age of the gravels and associated silts.[2] Certain "red beds" above the Cretaceous in this region are referred by the bureau mentioned to the late Tertiary, but the deposits of this age are usually merely local gravel fans beneath the loess.

[1] Charles P. Berkey and Walter Granger, "Later Sediments of the Desert Basins of Central Mongolia," *Amer. Mus. Nat. Hist. Novitates, No. 77* (1923), pp. 16.

Charles P. Berkey and Frederick K. Morris, "Basin Structures in Mongolia," *Bull. Amer. Mus. Nat. Hist.*, Vol. LI, Art. 5 (1924), pp. 103–27; "Structural Elements of the Old Rock Floor of the Gobi Region," *Amer. Mus. Nat. Hist. Novitates, No. 135* (1924), pp. 16; "Peneplanes of Mongolia," *ibid., No. 136* (1924), pp. 11.

Charles P. Berkey, "Geological Reconnaissance in Central Mongolia," *Nat. Hist.*, Vol. XXIV, pp. 160–73, 1924.

[2] P. L. Yuen, "Geological Notes on East Kansu," *Bull. Geol. Society of China*. Vol. IV, No. 1 (1925), pp. 1–28.

STRUCTURE

The North Shensi Basin is an oval area measuring 400 miles from north to south and 275 miles from east to west. The present rim consists mainly of uplifted fault blocks, usually capped with the Ki-chou (Cambro-Ordovician) limestone. On the flanks of this limestone, above an erosion unconformity, lies the coal-bearing Shansi formation. The latter is found on the east, south, and west, and probably also on the north, and dips steeply inward toward the center of the basin. The succeeding Pu-hsien was recognized only on the east and south. The Jurassic beds follow successively above the Pu-hsien, from east to west, with a nearly uniform westward dip of about 50 feet per mile until the lower beds, if not subject to thinning (of which there is no evidence), are 10,000 feet or more below the surface. They are not repeated on the west side of the basin, but apparently abut against faults which have brought the underlying Shan-si and Ki-chou to the surface, where they were beveled to the level of the Jurassic during the Cretaceous peneplanation. A recurrence of faulting, especially on the east and south, took place in the Quaternary and continued almost to the present time, resulting in the further elevation of the mountains of western Shansi and central Shensi.

AN EVALUATION OF THE EVIDENCE OF LIFE IN THE ARCHEAN

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ABSTRACT

A brief survey shows the indirect character of the evidence of life in the Archean. In the same category may be placed the evidence for algal life in the Archean iron-bearing formation of Minnesota, because definite data are lacking and filamentous algal forms are not generally preserved even in algal reefs. Organic-like structures, simulating algae, fungi, and worm-burrows, of inorganic osmotic origin, open up possibilities of misinterpretation of filamentous fossil forms.

The purpose of this paper is twofold: first, to question some of the evidence for the existence of algal life in the Archean iron-bearing Soudan formation of the Vermilion district, Minnesota, and secondly, to place before geologists the fact that organic-like forms, simulating fungi, algae, and worm-burrows, may be produced by inorganic means and in such a manner that their natural formation is probable.

EVIDENCE OF LIFE IN THE PRE-CAMBRIAN

It is to be noted that the evidence for, but not the occurrence of, life in the Archean is questioned. Prior to the publication of papers by Gruner,[1] the evidence of life in the Archean was almost all of an inferential character, but sufficiently convincing to be accepted generally by geologists. Evidence of a more direct nature, perhaps, is that given by Logan and Dawson,[2] as early as 1864, for the organic origin of Eozoön canadense, in the "definite, ramifying, cylindrical forms penetrating a matrix of limestone" found in the Grenville rocks of Ontario. As is well known, their conclusions have not obtained general acceptance, and since the Grenville rocks possibly may be of Huronian age,[3] the significance of their organic content may not bear directly on the question of life in the Archean.

[1] W. J. Gruner, *Journal of Geology*, Vol. XXXIII, p. 152; Vol. XXXI, p. 146.

[2] Logan and Dawson, *American Journal of Science*, (2), Vol. XLIV, pp. 367–76.

[3] T. Quirke, *Bulletin Geology Society of America*, Vol. XXXV (1924), pp. 89–90.

The indirect evidence of life in the Archean is based on (1) the apparent presence of favorable environmental factors, (2) the necessity of precursors for the algal life of the Proterozoic and the relatively well-developed life of the Cambrian, (3) the presence of graphite and carbon in limestones, slates, and even in the Soudan formation, (4) the presence of solid hydrocarbons, as anthroxolite, in Archean rocks of Ontario,[1] and (5) on the very doubtful significance of limestones and iron formations themselves.

Of these the presence of carbon may be of questionable value. Various inorganic sources of carbon have been suggested by Moore,[2] and Winchell[3] has explained how carbon may be deposited from magmatic gases. Graphite imbedded in feldspars has been found in Greenland[4] in iron-bearing basalts and also in other igneous rocks elsewhere. Thus graphite in igneous rocks, or in rocks associated with them, may be of inorganic origin. Moreover, carbon of a hydrocarbon parentage may have migrated from overlying rocks. However, the remaining indirect evidence suggests that life did exist in the Archean, but absolute proof thereof has been wanting.

In the Proterozoic rocks the evidence of life is hardly open to question.[5] Structures generally considered of algal origin occur in reef-like masses in the Lower[6] and Upper Huronian (Biwabik iron formation)[7] of the Lake Superior district, in the Belt series of Montana,[8] and in limestones in Hudson's Bay districts.[9] Many of the calcareous structures in Montana have been referred by Walcott[10] to blue-green algae. The forms of individual algae are not

[1] E. S. Moore, *Transactions Royal Society Canada*, Sec. IV (1925), pp. 21–26.

[2] Moore, *op. cit.*

[3] A. N. Winchell, *Economic Geology*, Vol. VI (1911), pp. 218–30.

[4] F. W. Clarke, *U.S. Geol. Survey Bulletin 770*, p. 331.

[5] Pirsson and Schuchert, *Historical Geology*, Vol. II, p. 573.

[6] W. H. Twenhofel, *American Journal of Science*, Vol. XLVIII (1919), p. 341.

[7] F. F. Grout and T. M. Broderick, *American Journal of Science*, Vol. XLVIII (1919), p. 199.

[8] C. D. Walcott, *Smithsonian Miscellaneous Publications No. 2271* (1914), pp. 77–156.

[9] E. S. Moore, *Journal of Geology*, Vol. XXVI (1916), p. 423; C. K. Leith, *Journal of Geology*, Vol. V, p. 240.

[10] Walcott, *op. cit.*

known to have been found, but only the mass effects of assumed colonies of algae. These mass effects are so consistent in a given formation, show geographical variations, and so resemble structures now being formed by algae that they are best referred to an algal origin. Besides, the abundant presence of carbon in unmetamorphosed limestones and black shales clearly suggests life. Most identifications of Proterozoic fossils of an organization higher than algae have been made with some reservations. Wormlike burrows and linguloid types of marine invertebrates have been reported, but the former may have been developed by inorganic processes and the identification of the latter must await confirmation. *Beltina danai* has not yet been accepted by all as a crustacean.

The recently reported occurrence[1] of fossils of the most fragile, filamentous types of algae in the Soudan cherts, coupled with the fact of the relative scarcity or total absence of similar forms in most formations, even those of the later geologic systems, is a matter of great interest and importance and one deserving of very close scrutiny. The data regarding the fossils are not numerous. The analysis of the observed facts has not been very rigorous, and their interpretation seems open to question. It is suggested that the evidence permits of an interpretation postulating an organic origin. That organic-like forms, wholly of inorganic origin, may be produced in nature has long been known. It may be that some, perhaps all, of the reported Archean fossils developed in an inorganic way.

The discovery that many fungoidal osmotic growths may be produced under conditions which seem probable in nature opens up still further inorganic interpretations of structures found in rocks. Osmotic growths of various types, illustrated herein, were obtained accidentally during the course of investigations on the formation of ferrous silicates (the mineral greenalite) which occur in the Biwabik iron formation of Upper Huronian age. The types of growths and methods of formation are quite well known to chemists and have been described by several writers, but do not seem to have been very seriously considered by geologists.

[1] W. J. Gruner, *Journal of Geology*, Vol. XXXIII, p. 152.

LACK OF DEFINITE EVIDENCE FOR THE ORGANIC ORIGIN OF STRUCTURES IN THE SOUDAN FORMATION

The structures in the Soudan formation reported by Gruner as organic are described as black or brown, and of "wormlike shapes, branching forms, and intricately winding."[1] Professor Josephine Tilden of the University of Minnesota is stated to have examined the slides and to have reported that "she finds the shapes and sizes of the *organisms* resemble very closely those of certain blue-green algae."

The photographs of the slides show organic-like structures. A reading of Gruner's paper suggests that the structures were assumed to be organic without the attempt being made to discover if similar forms might not develop through inorganic processes, and without a close search for another organic structure which should be present if the forms described were really of organic origin. The mere similarity in shape and size cannot be considered conclusive. Such features as cross-walls (septae), spores, and cysts, which are common to modern blue-green algae,[2] do not seem to be present. Algal spores are relatively dense,[3] and therefore might be expected to be preserved as well as the more perishable filamentous tubes. Biologists state that only the siphon type of algae is without cross-walls, but these algae are identifiable by other features. Apparent cross-walls, however, need careful study, as they may be produced inorganically in osmotic growths, and very similar structures are shown in a fine tubule in Figure 4.

The difference in size between the Soudan structures and living blue-green algae is perhaps important. The structures found in pebbles of the Ogishke conglomerate, and apparently derived from the Soudan formation,[4] when magnified 190 times (0.005 mm. and less in diameter) are as large as the living algae, to which they seem most nearly related, when the latter have been magnified 2,200 times. A similar difference in dimensions seems to obtain between

[1] Gruner, *loc. cit.*

[2] Professor E. M. Gilbert, University of Wisconsin, personal communication.

[3] *Ibid.*

[4] W. J. Gruner, *Journal of Geology*, Vol. XXXI, p. 146.

the "fossil bacteria"[1] found in the Biwabik formation and actual bacteria.[2] Osmotic growths have been produced whose filaments have a diameter of less than .01 mm., dimensions approaching those of the Soudan structures, and since these resemble algae in shape, it would seem that such criteria alone are inconclusive for identification purposes. If it be assumed that pre-Cambrian algae attained larger dimensions than their existing nearest relatives, their distinction from osmotic growths on a basis of size becomes more difficult.

FACTORS UNFAVORABLE TO THE PRESERVATION OF FILAMENTOUS ALGAE IN THE SOUDAN FORMATION AND IN THE PRE-CAMBRIAN IN GENERAL

There would be little point in basing an argument on factors hindering the preservation of delicate algal structures in an Archean rock were the proof of such an origin for them complete. One could merely marvel how such delicate forms could have escaped the various factors acting against preservation. It is true the finely crystalline cherts of the Soudan may have been especially favorable for such preservation, but even these have undergone some recrystallization since deposition, and amphiboles and magnetite have been developed in associated rocks.

The Soudan iron formation as described by Van Hise and Leith[3] is intimately related to the underlying Ely (volcanic) greenstones in which it is infolded. Near the base of the formation are thin graphitic slates interstratified with, or occurring below, the jaspers. "Some jasper belts are clearly interbedded with successive basalt extrusives," and "many are more closely associated with intrusive and extrusive porphyries than with greenstones." The formation is intruded in places by the Giants Range granite. The silica and iron are supposed to have been contributed either directly to the sea from magmatic sources or by the reaction of hot submarine flows with the sea water.

Such an origin for the iron formation does not preclude the possible existence of life in the seas. Conditions may easily be imagined which would favor the killing off of such life and its rapid burial and

[1] W. J. Gruner, *Minnesota Geol. Survey Bulletin 19*, Plate XI, p. 60.

[2] E. C. Harder, *U.S. Geol. Survey Prof. Paper 113*, 1919.

[3] C. R. Van Hise and C. K. Leith, *U.S. Geol. Survey Monograph 52*, pp. 122–28.

preservation as fossils. However, the occurrence of the reported algae no more indicates an algal origin for the iron formation than the bryozoa in the Clinton ores prove a bryozoan origin for the latter. On the other hand, if the volcanic origin of the iron formation is correct, the environment, as will be shown later, may have been exceptionally favorable to the development of osmotic growths. Both algal and osmotic forms might then be expected.

The graphitic slates in the Soudan formation suggested an organic origin to Van Hise and Leith. Proof of this was not attempted. Assuming an organic origin as correct, and taking note of the fact that the slaty bands would be less competent than the jaspers and cherts under stress, it may be inferred that the metamorphic changes have been sufficiently great to destroy all trace of delicate filaments of algal origin.

No evidence of minute filamentous growths has been reported in any of the Proterozoic Lake Superior algal limestones, or in such limestones where replaced by silica. These algae are of the "encrusting type, and lime carbonate does not enter the tissues of the plant,"[1] but the conditions must have been such as to favor preservation of the plant structures responsible for the precipitation.

On the other hand, if the structures in the Soudan rocks are osmotic and inorganic, how may we explain the equally amazing fact of their preservation? The thickness and strength of the forms produced in the laboratory may possibly aid in an explanation. Or again, the environmental conditions during their formation may be of more vital importance. On a sea floor being disturbed by vulcanism through a considerable period of time, the opportunities seem greater for osmotic growths to flourish than for algae.

OSMOTIC GROWTHS

Fungoidal precipitation structures may be made easily in the laboratory by dropping crystals of ferrous sulphate or other soluble metallic salts into a solution of water glass, sodium silicate, and allowing the salt to diffuse. Other methods include the use of solutions of alkaline phosphates and carbonates, with salts of metals or alkaline earths, and solutions of ferro or ferricyanide with gelatine,

[1] W. H. Twenhofel, *op. cit.*, p. 342.

sodium chloride, and metals themselves. The time required for the growths to form from the immersed salts or metals varies from a few minutes to several hours. Since we are concerned here with substances which will form rocks similar to those of the Soudan iron formation, attention will be confined to the ferrous and ferric silicate

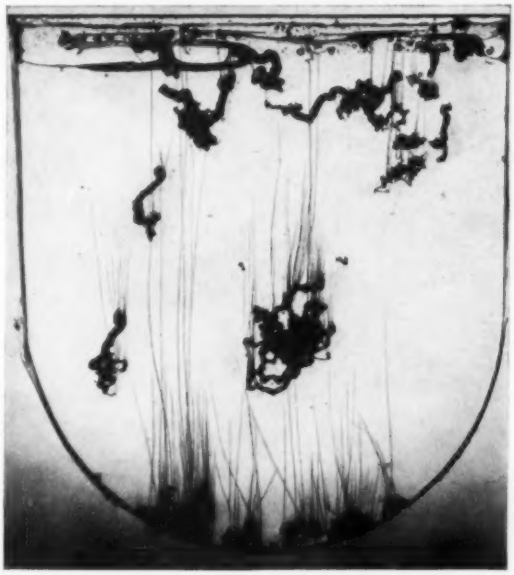

FIG. 1.—Ferrous silicate osmotic growths prepared from crystals of ferrous sulphate and concentrated water glass. The crystals are now represented by the membrane-inclosed nuclei from which the tubes have grown. About natural size.

growths. Such growths, known as the "silica garden" type of precipitate, were first produced by Glauber and were described by Böttiger[1] and Mulder[2] as early as 1837 and 1841. Investigation of the literature shows that the chemistry of the phenomenon has been studied by many.[3] The morphological as well as the biological simi-

[1] R. Böttiger, *Journal für praktische Chemie*, Vol. I (1837), pp. 10, 60.

[2] G. J. Mulder, *Journal für praktische Chemie*, Vol. I (1841), pp. 22, 4.

[3] J. W. Mellor, *Comprehensive Treatise, Inorganic Chemistry*, Vol. VI, C. Part II; L. Doveri, *Annales de chemie et de physique*, Vol. II (1822), pp. 21, 40; B. Von Ammon, *Ueber einige Silikate der Alkalien und Erden*, Köln, 1862; W. Hennis *Ueber die Reaktion zwischen Alkalisilicaten Schwermetallsalzen*, Erlangen, 1906.

larity to organisms of the forms produced in various ways has been noted particularly by R. S. Lillie[1] and S. Leduc.[2] The latter has elaborated upon them in his book, *The Mechanism of Life*, a volume, however, with which geologists do not seem to be familiar. The term "osmotic growth" is one introduced by Leduc.

Many variations in osmotic growths may be obtained by slightly different procedures. These, with the results of each, will be briefly

FIG. 2.—Ferrous silicate osmotic growths from ferrous sulphate salt in concentrated water glass, grown on a glass plate. Note winding tubules. ×10. Black rings in photograph are bubbles.

summarized. The alkaline silicate used in the experiments was commercial water glass ($Na_2O.3SiO_2$), with a specific gravity of 1.402.

1. *Concentrated water glass and ferrous sulphate crystals.*—In concentrated water glass, ferrous sulphate crystals give rise to green winding tubules, simulating worm-burrows to a high degree (Figs. 1 and 2). These "take root" in a rounded, bulblike membrane which forms around the crystal soon after immersion. At irregular intervals along them finer and straighter tubules burst forth and rise

[1] R. S. Lillie, *Biology Bulletin*, Vol. XXXIII, No. 3 (1917), pp. 135–86; *Biology Bulletin*, Vol. XXXVI (1919), pp. 225–72; *Science Monthly*, Vol. XIV (1922), p. 113.

[2] Stephane Leduc, Nantes, *The Mechanism of Life*, New York, Rebman Co., 1914.

toward the surface of the liquid, tapering slightly upward. The coarser tubules, as a rule, have many irregular volutions and show a greater tendency to branch. Annular-like rings may be formed in these (Fig. 3), apparently due to their more or less rhythmical

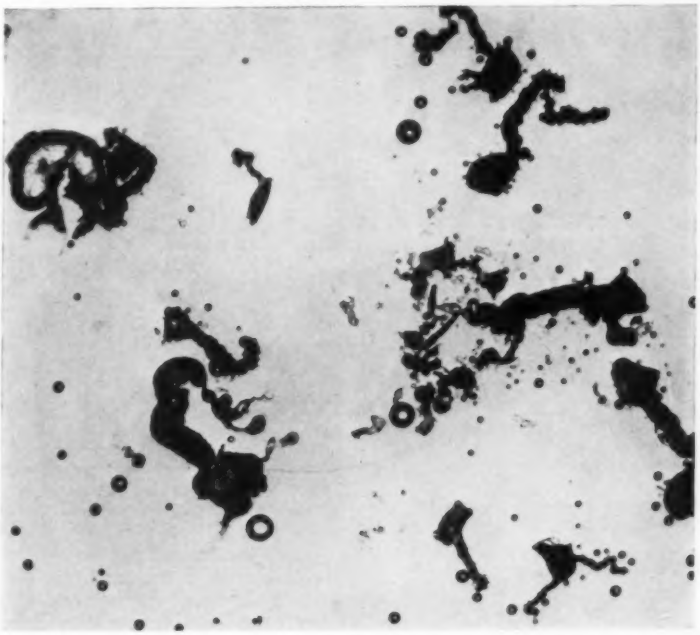

FIG. 3.—Ferrous silicate osmotic growths prepared on a glass plate from ferrous sulphate salt and concentrated water glass. Note annular rings and small protuberances. ×7. Black rings in photograph are air bubbles.

growth. The lengths of the larger tubules are generally small, 3–4 cm.; the finer ones are limited in length only by the depth of the solution and the supply of the salt. When grown in a thin film of concentrated water glass between two glass plates, the tubules follow a very tortuous path (Fig. 2), having less constant diameters and often winding about on themselves.

2. *Dilute solutions of water glass.*—In dilute solutions of water glass (with a minimum of 5 per cent concentration) ferrous salts

yield growths of a fine fibrous type with a distinct seaweed appearance. These are also tubular and essentially like the fine branches of the vermiform structures. In diameter they range from 0.5 mm. to

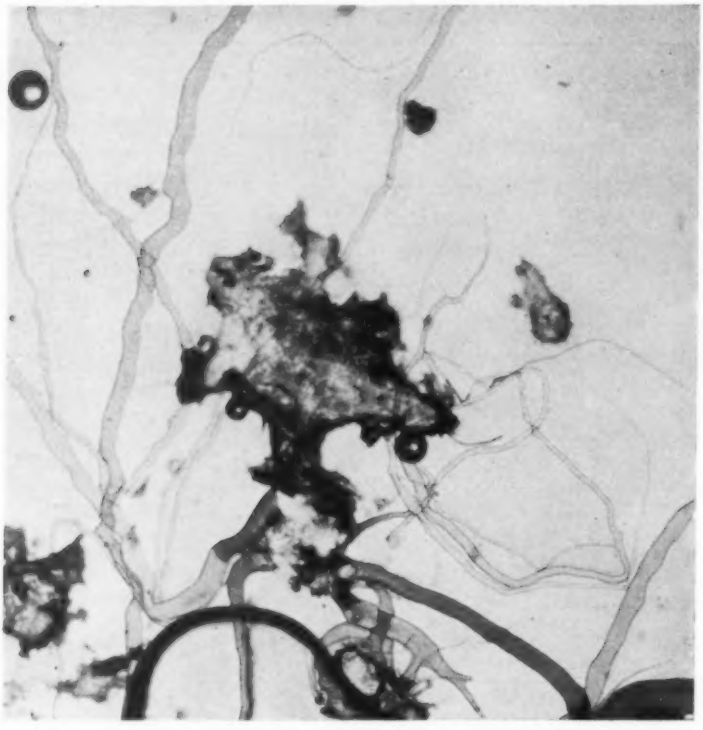

FIG. 4.—Ferrous silicate growths formed in 25 per cent concentrated water glass between two glass plates. Note cell-like pattern in fine tubule at right center. ×22.

slightly less than 0.01 mm. Growths made in 10–25 per cent concentrated water glass in narrow celluloid dishes are of a rectangular type, following first a horizontal and then a vertical direction, at the same time winding in spirals, as the tendrils of a vine. The rectangular pattern seems due in part to the walls of the container to which the growths become attached. The habit of the growths of attaching themselves to any solid particles in their vicinity is great

and suggests a manner in which infinite variations might arise. In thin films of dilute water glass fine crystals of the salt dissolve and diffuse rapidly, giving growths which branch, as illustrated by the

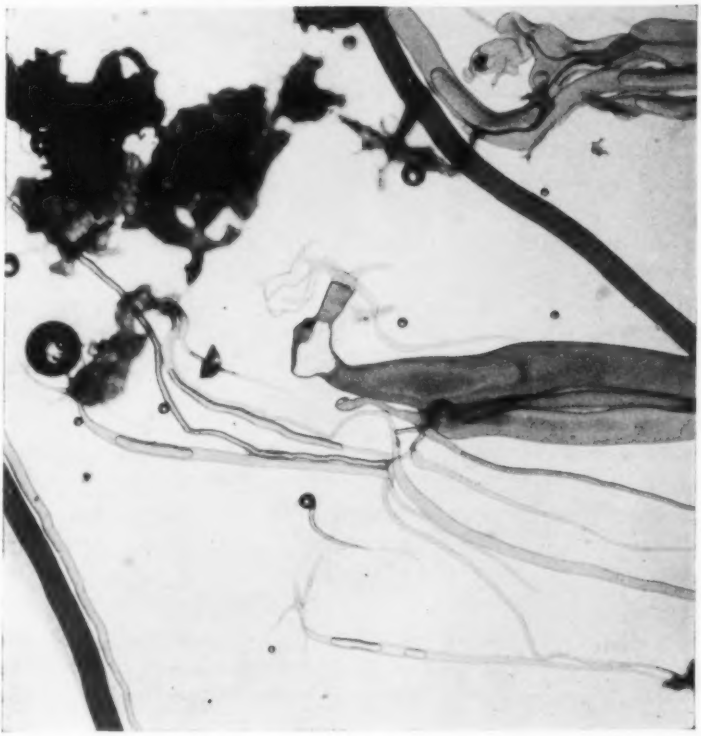

FIG. 5.—Ferrous silicate growths formed in 25 per cent concentrated water glass between two glass plates. Note forklike prongs developed on some tubes. ×25. Black rings are air bubbles.

prongs and forks of Figures 4 and 5. Structures resembling cross-walls also appear within the tubules, as in Figure 4.

3. *Variations in concentration of solutions.*—Variations may be produced in osmotic growths by local changes in the concentration of solutions used. These may be made in several ways, and yield in each case somewhat different results. By sowing crystals of ferrous

sulphate in a layer of concentrated water glass and then adding more dilute layers of the solution above, the forms produced tend to branch at the surfaces of separation of the liquids. With salts which enter solution more rapidly than ferrous sulphate, as ferric chloride, knots and swellings result at the contact of the two liquids.[1]

When many of the growths reach the surface of the liquid they spread out and form a thin crust to which all the "shoots" at this horizon become attached. The ferrous silicates soon become oxidized. If the surface of the water glass be covered with a layer of distilled water, a mushroom-like form arises in place of the crust.[2] Rounded bulblike terminal organs may be obtained by diluting the solution a hundred fold or more after the growths have reached a considerable size.[3] Also, when the solution around a cellular membrane is suddenly diluted, "it bursts by a process of dehiscence and projects into the liquid a part of its contents, which may then become separate vesicles."[4] Lillie[5] also produced this same phenomenon. The experiment demonstrates very well the part played by osmosis in the production of the structures.

4. *Growths formed in sand and clay.*—Fine sands were sown with small crystals of ferrous sulphate and saturated with a dilute solution of water glass. Fine fibrous growths formed among the grains and ultimately grew out and upward between the openings into the pure solution.

Clay was mixed with dilute water glass to a consistency of a thick paste, and crystals of the same salt were carefully inserted and covered. After hardening, the mass was broken open, revealing winding wormlike casts which were formed by osmotic growths. The power of the growths to force themselves through fine sediments is thus great, and compares favorably with the similar feat performed by vegetative roots.

5. *Growths in mixtures of alkaline phosphate and silicate.*—With a mixture of dibasic sodium phosphate and water glass, ferric chloride salts give rise to find wormlike structures with great rapidity. From the tubules fine spiral loops shoot out periodically, almost

[1] Leduc, *op. cit.*, pp. 131–32.
[2] *Ibid.*
[3] *Ibid.*
[4] *Ibid.*
[5] R. S. Lillie, *Biology Bulletin*, Vol. XXXVI, p. 255.

instantly assuming a length of 1–2 cm. (Fig. 6). Ferrous sulphate in the same solutions yields very wavy tubules, as illustrated in the same figure.

6. *Growths from ferrous solutions and water glass.*—To avoid the rather artificial method of dropping crystals of a ferrous salt into a

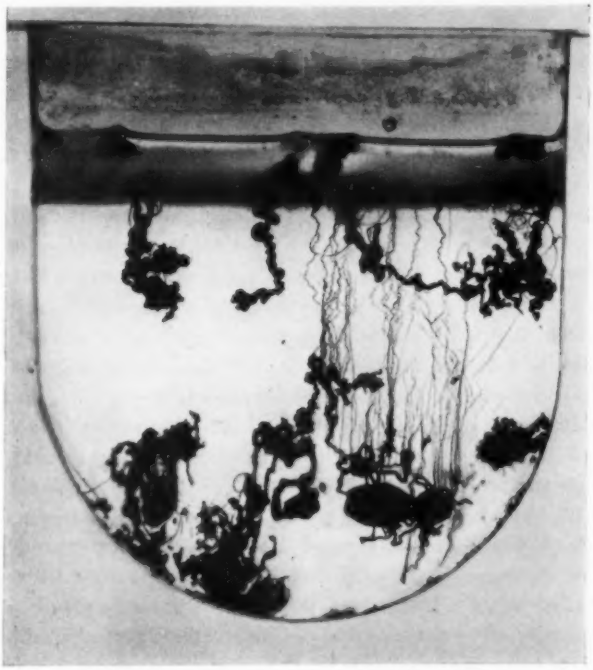

FIG. 6.—Ferric and ferrous silicate and phosphate osmotic growths in a layered solution. The coarser wormlike forms are ferric silicate or phosphate, the finer spirally winding forms are ferrous silicate or phosphate. The silicates were formed in the lower half, and phosphates in the upper. Natural size.

solution of water glass, a concentrated solution of ferrous chloride was allowed to diffuse into water glass through a fine capillary tube inserted below the silicate solution. A dark-green semipermeable membrane formed immediately about the opening, grew and extended to a considerable size, and from it, in time, fine tubular

shoots broke forth which resembled those formed by the crystal method.

By puncturing the membrane with a needle and drawing the latter away through the silicate solution, a find delicate tubule may be drawn out which will follow the end of the rod for many centimeters. That these are actually tubular growths is proved by the fact that, after being detached from the rod, they will continue to grow as tubules by osmotic processes. This experiment is very suggestive regarding occurrences in nature. Should conditions be such as to yield these large vesicles of ferrous silicate, any particles of sediment coming in contact with them might act as the needle, puncturing the vesicle and drawing out fine tubules as they passed.

Inserting ferrous solution as globular masses in water glass by means of a pipette yields practically the same results as diffusion of the iron solution through a capillary tube. An added feature, however, is the occurrence of columnar coralline masses consisting of clusters of fine tubules growing upward together and joined to one another by gelatinous silica. These resemble forms obtained with calcium salts in sodium carbonate solution (Fig. 7).

Attention should also be called to the rounded vesicles or cells formed by the slow bubbling or dropping of a ferrous liquid into an alkaline silicate solution. These are similar to the granular precipitates obtained by Van Hise and Leith[1] in their reproduction of greenalite, which were attributed to surface tension phenomena and the low crystallizing power of the precipitate. Some features of the greenalite granules themselves, namely, the fine tails often connecting granules, suggest that some of them were originally osmotic cells which were ruptured either by the diffusion pressure of the contained liquid or by dehiscence following dilution of the surrounding liquid, as described above. The tails would form by the reaction of the outward-moving ferrous liquid and an inclosing silicate solution.

CHEMISTRY

Since geologists are not concerned particularly with the chemical processes which control the morphology of the organic-like growths, this subject will be touched only briefly. Their production seems to

[1] C. R. Van Hise and C. K. Leith, *op. cit.*, pp. 522–25.

depend on the formation of a colloidal, semipermeable membrane by the reaction of the two salts. This forms around the introduced salt or liquid, and "opposes different resistances to the passage of

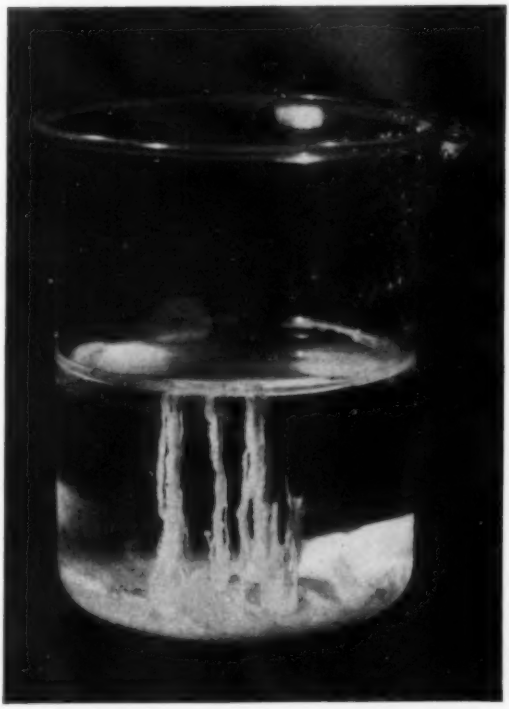

FIG. 7.—Calcium carbonate coralline osmotic growths formed from $CaCl_2$ salt and Na_2CO_3 saturated solution. Similar growths of ferrous silicate may be made. Natural size.

water and of the various substances in solution, being very permeable to water but much less to the different solutes." Within the cellular membrane the salt, entering into solution, exerts a high solution or diffusion pressure which is sufficiently great in some cases to distend it. When the diffusion pressure is sufficient the membrane may be broken, and naturally at the weakest points first. Such points of weakness may be localized by the adherence of small air

bubbles on the crystals. These, however, are not always required, as the fine tubules break out at other points.

Once such an opening forms in the membrane the diffusion pressure, and probably other factors, seem sufficient to set up a current strong enough to keep open a passage through the tubes, either intermittently or until the pressure declines. Lillie[1] has observed the fine colloidal particles of the precipitate formed at the orifices of the tubes being carried out of the tubes like smoke from a chimney, and in part being deposited at the extremities. In his study of metallic ferricyanide precipitation structures Lillie concludes that the growths are essentially the product of local electrolysis combined with diffusion.

The composition of the growths formed from ferrous salts and water glass has been shown by L. Doveri[2] to be a mixture of silicic acid and ferrous silicate and hydroxide. These growths are readily oxidized in the air to a dark brown. When still quite fresh, however, an X-ray pattern was obtained which shows the material to be at least partly crystalline and rhombohedral in character. The pattern differs radically from quartz or goethite, and is probably that of a ferrous silicate.

POSSIBILITIES OF OSMOTIC GROWTHS IN NATURE

To have osmotic growths form in an environment where silica and iron oxides or iron silicates were being deposited seems to require that we have sodium silicate (at least equal in concentration to a 5 per cent concentrated water glass) and either soluble iron salts or iron solutions, and that these be brought together in a suitable manner.

In nature, the general method by which different solutions may be brought together is that of different streams uniting or emptying into a standing body of water. This, by various reactions, gives flocculent or colloidal precipitates. There are, however, two methods which probably would favor the production of osmotic growths. One is by subaqueous springs or seepages through fine openings in

[1] R. S. Lillie, *Biology Bulletin* Vol. XXXIII, pp. 144-46.

[2] L. Doveri, *op. cit.*, p. 40.

hard or soft rock. The other is by local solution of part of the required constituents from freshly precipitated sediments, and the diffusion outward or upward of the solution through capillary openings until it comes in contact with a suitable precipitating agent. A third source for such solutions may be found in magmatic juices. To say which of these methods is likely to be the most common is not possible. Neither can we point to any specific case where any of these processes did produce osmotic growths. All of them seem possible; that of re-solution may offer more opportunities than the others.

The process of re-solution of a salt, under local conditions in sediments, and the diffusion of the resulting liquid to a zone where precipitation may occur, has long been looked on as a most probable occurrence, if not a fact, in sedimentation. Examples such as the de-cementation of a sand at one locality and the cementation at another, the growth of concretions of calcium carbonate and even silica may be mentioned. If such phenomena actually occur, then there seems little doubt that several opportunities for the production of osmotic growths exist in nature.

To account for alkaline silicates of sufficient concentration in standing bodies of water is perhaps difficult. Alkaline silicates are formed in weathering and by the reaction of alkaline carbonates on silicates. The presence of silica in alkaline-rich river waters is noted by Clarke.[1] By some it is held that silica is carried largely as a colloid rather than as an alkaline silicate in dilute natural solutions.[2] Magmatic sources may easily account for alkaline silicate solutions of varying concentrations. Van Hise and Leith[3] have shown experimentally that the introduction of a hot lava into sea water will give rise to alkaline silicates. The association of siliceous iron formations of the Lake Superior district with submarine lavas has suggested to these writers a distinct genetic relation. Others[4] have questioned the theory as to the adequacy of the process to yield sufficient iron, but there are many arguments which show

[1] F. W. Clarke, *op. cit.*, p. 11.

[2] Kahlenbergh and Lincoln, *Journal Phys. Chem.*, Vol. II (1898), p. 90.

[3] *U.S. Geol. Survey Monograph 52.*

[4] W. J. Gruner, *op. cit.*, p. 51.

the inadequacy of any other processes.[1] For the purpose of the writer the original source of the iron matters not, but volcanic contributions of iron solutions or acid solutions capable of dissolving iron must be admitted as possible. Since the iron is there, any process of re-solution will also satisfy the requirements. Such processes of re-solution and local precipitation have been advocated by several writers[2] to account for certain layers of pure ferric oxide in the iron formations, or of granular layers much richer in iron than others. With vulcanism active in the vicinity of such deposits and during their formation, the possibilities for re-solution of iron by acid waters are greatly enhanced. (Cf. HCl content of volcanic waters, Clarke, *Bulletin* 770, p. 201.) Such conditions would clearly be favorable to the formation of osmotic growths.

If we assume, then, that some of the siliceous iron formations, like the Soudan, were formed originally by contributions from volcanic sources, by direct submarine volcanic emanations, or by reactions of hot lavas with sea water, the reagents, solutions of alkaline silicate and of iron, may be easily accounted for. It is true that salt water, if such were present, would tend to throw the silica out of solution from the alkaline silicate, but it is improbable that this would be instantaneous and complete at first. Trial experiments show that a considerable amount of salt solution may be added to water glass and still leave sufficient sodium silicate in solution for the formation of osmotic growths with iron salts. The *modus operandi* could then be very similar to that already sketched above.

SIMILARITIES BETWEEN SOME OSMOTIC GROWTHS AND THE ALGAE OF THE SOUDAN IRON FORMATION

The similarity between some osmotic growths of the ferrous silicate types and the forms found in the Soudan iron formation may be seen by comparing the accompanying photographs with those of Gruner. Both show fine filamentous tubules, straight or winding, and many arise from a bulblike mass or nucelus. Both branch in several directions or curve about themselves. The relative simplicity of each is a common feature. The slight tapering tendency of the

[1] C. K. Leith, *Economic Geology*, Vol. XIX, p. 385.

[2] F. F. Grout and Broderick, *Minnesota Geological Surv. Bulletin 17*, p. 47.

osmotic growths might be considered as a difference, though many vegetative growths have this habit. The compounds used to produce the artificial forms are ones which may form chert and iron oxides, the dominant constituents of the Soudan formation.

In size the Soudan forms have diameters which range up to approximately 0.005 mm. as measured from photographs. The smallest diameters obtained so far are slightly less than 0.01 mm. While this discrepancy is sufficient to question the similar identity of the forms, it should be remembered that the conditions under which the iron formation was formed were not absolutely reproduced in the laboratory. Pressure and temperature are factors which may account for slight differences. Increase of temperature, so far as determined, aids materially only in the rate of growth. Temperatures of 40° C. produce no effects appreciably different from those produced at room temperatures. Pressure effects, however, have not yet been studied, and the great variety of concentrations of solutions possible in nature, besides, is another factor to be considered. It is even possible that a further study of the Soudan forms will reveal other differences in morphology, and a study of these must take into account both algal and osmotic morphology.

In so far as the Soudan forms have been referred to a type of blue-green algae, it is interesting to note that Lillie,[1] in describing the growths of ferrous ferricyanide on an iron wire, says they "resemble blue-green algae." In comparing the precipitation growths to organisms the same writer says:

> The essential basis for this resemblance is undoubtedly the formation of semipermeable membranes; these, by preventing diffusion, furnish the conditions for the osmotic entrance of water into the various membrane-enclosed spaces, ... for a more or less definite localization of osmotic processes, and the direction of flow of solution results; hence the deposition of a precipitate is also localized and a corresponding definite structure is formed, which resembles that of simple vegetative growths, because of the importance of the osmotic factor in both cases.[2]

The formation of cell-like walls or septae in fine tubules by Leduc has been mentioned already. While such do not seem to appear in the Soudan forms, their presence may be of doubtful value,

[1] R. S. Lillie, *Science Monthly*, Vol. XIV (1922), pp. 113–30.

[2] R. S. Lillie, *Biology Bulletin*, Vol. XXXVI, p. 234.

and unless distinct morphological features characteristic of organisms can be found, the question of origin must be left open. It is not the wish of the writer to overemphasize the points of similarity between various osmotic growths and algae or other vegetative forms, nor to imply that the Soudan structures are necessarily osmotic. They may be either.

Since algal-like forms have also been found by Gruner in the Biwabik iron formation, within which algal reef structures occur, is it a fair conclusion that the Soudan forms have the same organic origin as those of the Biwabik? Such a corollary would not be demonstrated even if the latter can be proved definitely organic.

In this connection it is interesting to compare some of the colloform structures with which "algae" are associated, found by Gruner[1] in the Biwabik formation (Plate IIIA, *Bulletin* 19) and similar colloform structures found by Knopf[2] and illustrated recently by Boydell.[3] The latter writes: "The bursting of colloidal membranes by osmotic pressure by Knopf to account for the curved and typically colloform particles of wood tin, resembling in some cases broken annuli which occur in the Tertiary rhyolites of Northern Nevada."

Outside the "scallops" of the Biwabik colloform structure referred to are minute winding and branching forms which, from the photographs, appear very similar to the types of osmotic growths illustrated herein. They are attributed by Gruner to micro-organisms. If the colloform structure is due to osmotic effects, it seems quite possible that the winding forms may have the same origin.

CONCLUSIONS

The evidence of life in the Archean and the pre-Cambrian in general is largely of an indirect character. The most notable exception in the Proterozoic is that of the widespread algal reef structures. The more recent evidence produced by Gruner to prove the existence of algae in the Archean is open to question on three grounds: first, because of the lack of data pointing definitely to an organic origin for the organic-like structures; secondly, because filamentous algal

[1] W. J. Gruner, *Minnesota Geol. Survey Bulletin 19*, Plate IIIA.

[2] Knopf, *Economic Geology*, Vol. II (1916), p. 658.

[3] H. C. Boydell, *Economic Geology*, Vol. XXI, pp. 47–48, Figure 12.

structures have not been found in algal reefs, and the metamorphism which the Archean rocks have undergone most probably would have destroyed them; and thirdly, because the structures may be inorganic osmotic growths.

Methods of producing osmotic growths are described. These growths have distinct vermiform, fungoidal, and coralline shapes. Some are very similar to the structures described as organic by Gruner.

The possibilities that osmotic growths may be produced in nature are considered, particularly in an environment where deposition of a siliceous iron formation, as the Soudan, occurs. Local conditions of re-solution of iron-bearing sediments are used as a part of the process, these solutions entering and reacting with solutions of sodium silicate which may be derived from subaqueous extrusions of lava or from magmatic sources.

In the Biwabik (Upper Huronian) iron formation some organic-like forms resembling those of the Archean are associated with colloform structures. The latter may be osmotic in origin, as probably are other colloform structures, and the same origin may hold for the algal-like forms.

The final proof of the origin of the Archean forms apparently must await the discovery of more definite evidence. Both an organic and an inorganic origin may be possible. The similarity between osmotic and certain organic forms is such that geologists should consider both in interpreting the origin of filamentous fossil forms. In a later paper the writer hopes to deal more broadly with the rôle which osmotic growth plays in geology. There is obviously a wide and interesting field for research along these lines.

THE RECOGNITION OF MINERALS AND THE DETERMINATION OF THEIR PROPORTIONS IN CRUSHED ROCKS

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ABSTRACT

The constituents of crushed rocks are etched with hydrofluoric acid and are then stained. By their different appearances after this treatment the minerals may be recognized and the composition of the rock may be determined by grain counts. The ferromagnesian minerals are recognized by their color and other optical properties, the plagioclases show an opaque stained mantle, the potash feldspar is corroded but transparent, and the quartz is unaffected. If the grains are immersed in an oil having a refractive index near that of Canada balsam, a further aid in the separation is obtained.

Thin sections of rocks are essential in the study of textures, but for the determination of rock minerals and percentage compositions they may be supplemented or even replaced by fragments of crushed rocks. Since the grains, in spite of careful sifting, vary somewhat in size, properties such as birefringence cannot be used in their determination, but many of the other optical properties, as color, refractive indexes, optical character, cleavage, orientation, etc., still remain. Besides these, chemical reactions and etching and staining may be applied. These tests, in some cases, may be made quantitatively and have an accuracy equal to, or even greater than, that obtainable from thin sections. It is a simple matter to analyze a considerable quantity of crushed material, while the expense of many thin sections is prohibitive and a single thin section may represent only a local phase.

The method described below depends upon etching, staining, and refractive indexes for the recognition of the minerals, and on grain counts for the determination of the percentage composition. Uniform-sized grains are obtained by crushing the rock, sifting *thoroughly*, and retaining the fines which pass through the 80-mesh sieve and are caught on the 100-mesh. This material is first quartered to small bulk, perhaps a half-gram. It is then placed in a lead dish contain-

ing 50 per cent hydrofluoric acid, and is allowed to stand for seven minutes, this period of time having been chosen after many experiments as most suitable for the material on hand. Too long etching dissolves potash feldspar, while too short etching does not attack the plagioclase. The acid attacks the feldspars, producing silicic acid, but quartz is practically unaffected in this short time. The material is now washed with a fine jet of water from a wash bottle, after which a strong solution of gentian violet is added and allowed to stand for ten minutes. The silicic acid produced by the action of the acid on the feldspars is thus stained. The fragments are again washed and are transferred to an object glass and gently dried over a small flame. The drying causes partial or complete dehydration of the silicic acid and leaves an opaque rim about the feldspars, especially about the plagioclases. If the etching is timed just right, one may get a coating of silicic acid on the plagioclases but not on the potash feldspars, although the latter are corroded.

The slide is now viewed under the microscope. The stained feldspars can be differentiated readily from the unstained quartz. With practice, microcline or orthoclase can be distinguished from the plagioclases by the etched outlines of the former and the opaque rims about the latter, but these characters are brought out better by adding a drop of an immersion oil which dissolves the stain. If the oil has an index of refraction of 1.537, the Becke line may be used as a check. Usually the ragged, angular outlines of the potash feldspars are sufficient. The ferromagnesian minerals, such as augite, hornblende, and biotite, are easily recognized by their usual properties.

The method may be made quantitative by counting the grains of the different minerals, using a grating micrometer eyepiece if desired. If the material is not scattered too thickly over the slide there is little trouble in counting the number of grains of each constituent in each quadrant of an eyepiece provided simply with cross-hairs. As many fields of view as desired may be taken, and the process repeated on more material if necessary.

The following points should be carefully noted:

1. The grains of the different minerals must be of uniform size in order that the grain count may have a quantitative value. Uni-

formity is dependent on the sifting, which should be continued until a small quantity of the material, viewed under the microscope, shows the grains to be of equal size. Fines through a 90-mesh sieve and caught on 100-mesh would be preferable to those sifted only through the 80 and retained on the 100, but even fines through the 60 and on the 100 may be used, although the accuracy is lowered.

2. A medium magnification (approximately 80 times) was found suitable when viewing grains of the size mentioned. With lower magnifications coarser material may be used, but such material would require longer etching, and furthermore, in fine-grained rocks, the constituent minerals might not be broken apart by such coarse crushing. With higher magnifications finer material may be taken, but there is danger of scratching the objective, since cover glasses cannot be used, for their weight alone may crush some of the etched minerals.

3. All the fines treated with hydrofluoric acid and stained should be placed on one slide. If only part is used, a differential separation of the minerals may be produced, since they are transferred from the lead vessel to the slide by means of a fine jet of water from the wash bottle, and some minerals, such as flaky biotite, are more readily transferred than others. The material viewed under the microscope should not be so abundant that the grains are crowded together and overlap. With medium magnification about 80 grains in the field were found convenient. The percentages determined by counting may be made perfectly accurate, the error in result depending only upon the inaccuracy of the proportions obtained by sifting.[1]

4. Microcline and orthoclase are more readily decomposed by hydrofluoric acid than are the plagioclases, and so the time of immersion in the acid must be long enough to produce the silicic acid rim on the plagioclases, but not long enough to break up the potash feldspars. The latter are in many cases considerably altered in the rock, and are thus rapidly decomposed. The time that the acid is allowed to act on the minerals is governed by the state of alteration. In some cases the weathering or alteration may have proceeded so

[1] Albert Johannsen and C. A. Merritt, "Comparative Losses in Crushing and Sifting Rock Minerals," *Journal of Geology*, Vol. XXXIV (1926), pp. 275–80.

far that the acid breaks up the potash feldspar before it attacks the plagioclase sufficiently to be of practical value. In these circumstances the total number of grains may be counted before treatment with the acid. They may then be treated as before and the grains again counted, disregarding the broken-up potash feldspar. The latter are then determined by the difference between the two grain counts.

5. Stains other than gentian violet may be used, though this stain was found satisfactory.

6. The drying of the material on the slide is essential to produce the opaqueness of the plagioclase, which is characteristic and of the utmost value in the identification. In fact, the staining may be omitted, though it is corroborative. The washing must precede the drying, since the heat hardens and cracks the silicic acid so that subsequent washing removes it.

7. The color is best seen by incident light.

8. Crystals of potassium-, sodium-, or calcium-fluosilicate were in many cases noticed on the slide. This was due to insufficient washing. The association of these crystals with certain mineral grains cannot be used in their determination, since the crystals have separated from the inclosing solution.

9. Careful washing is necessary to remove the hydrofluoric acid in order to protect the objective. If desired for protection, a cover glass may be fastened to the lower lens with cedar oil.

TREMATOPS THOMASI, A NEW AMPHIBIAN SPECIES FROM THE PERMIAN OF OKLAHOMA[1]

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ABSTRACT

The amphibian genus, *Trematops* Williston, has been represented until recently by a single specimen, a skull and associated skeleton from the Permian of Texas. The skull is unique among vertebrates in the presence of a median, unpaired opening that pierces the skull near its tip. The following description is of a skull from the Permian of Oklahoma that is similar to that from Texas in many details. However, the Oklahoma specimen shows the unpaired opening on the palate surface only. Another point of interest is the remarkably well preserved "turbinated" bone.

Some time ago, through the kindness of Mr. Hugh Thomas, then a student in the University of Missouri, the major part of a fossil amphibian skull was brought to the attention of the writer. The freshness of the breaks across the hard bone and matrix led to the hope that the rest of the skull and other remains might be found. With this in view the locality was visited in the summer of 1924 and the exact spot of the find located. It was learned here that the find had been made ten years earlier. Since that time a vast amount of slumping has completely buried the little gully from which the skull came. In the short time available for the investigation no further bone fragments were found, and it now seems advisable to make some record of the material at hand.

The remains came from the Clear Fork division of the Permian,[2] about 10 miles south and a little east of Snyder, Oklahoma. They consist of the anterior part of the skull and the attached lower jaws. The skull is complete from the anterior borders of the orbits forward. In addition there is preserved the right ramus of the mandible well

[1] M. G. Mehl, "Amphibian Remains from Permian Beds of Oklahoma," *Pan-American Geologist*, Vol. XLV (April, 1926), pp. 552–53 (abstract).

[2] This is the opinion of Dr. Charles N. Gould, as expressed in a personal communication to the writer.

toward its posterior end, and a corresponding length of the right lateral margin of the skull.

Williston[1] described the skull and associated skeletal parts of a unique amphibian, *Trematops milleri*, from the Permian of Texas. The Oklahoma specimen shows such marked similarities to the Texas form that the two are to be included, without doubt, in the same family, *Trematopsidae* Case. The Oklahoma specimen may be generically distinct, but the writer prefers to refer it to the genus *Trematops* until further evidence is forthcoming. It is to be called *Trematops thomasi*. The specific name is given in honor of Mr. Hugh Thomas, the discoverer.

Trematops thomasi, N. SP.

The skull is apparently somewhat smaller than the type of *Trematops*. It is subtriangular in outline as seen from above. The width of the posterior border seems to be but little less than the length along the median line. The regularity of the triangular outline is broken by a rather marked constriction of the skull immediately in front of the orbits.

The surface of the skull is marked by deep, rather sharply outlined pits that are, for the most part, nearly circular in outline. These pits and the narrow, rounded, separating ridges are not arranged in a definite pattern, except that there is a general diminution in size toward the margins of the skull. There is an entire absence of mucus canals.

OPENINGS IN THE SKULL

One of the striking peculiarities of *Trematops*, according to Willis-ron,[2] is an unpaired median opening at the anterior end of the nasals. To quote: "At the very front of the rostrum there is a rather small, but perfect, median, unpaired vacuity leading into a foramen in the middle of the palate below. I am at a loss to say what its real nature is. If not a medial narial opening, I cannot see why there

[1] S. W. Williston, "New or Little-Known Permian Vertebrates: *Trematops*, New Genus," *Journal of Geology*, Vol. XVII (1909), pp. 636–58.

[2] *Op. cit.*, pp. 640–41.

should be a palatal opening below it. It is not for the passage of teeth, as in some of the labyrinthodonts."

In the present specimen there is no suggestion of such an opening so far as the upper surface of the skull is concerned. The premaxillae

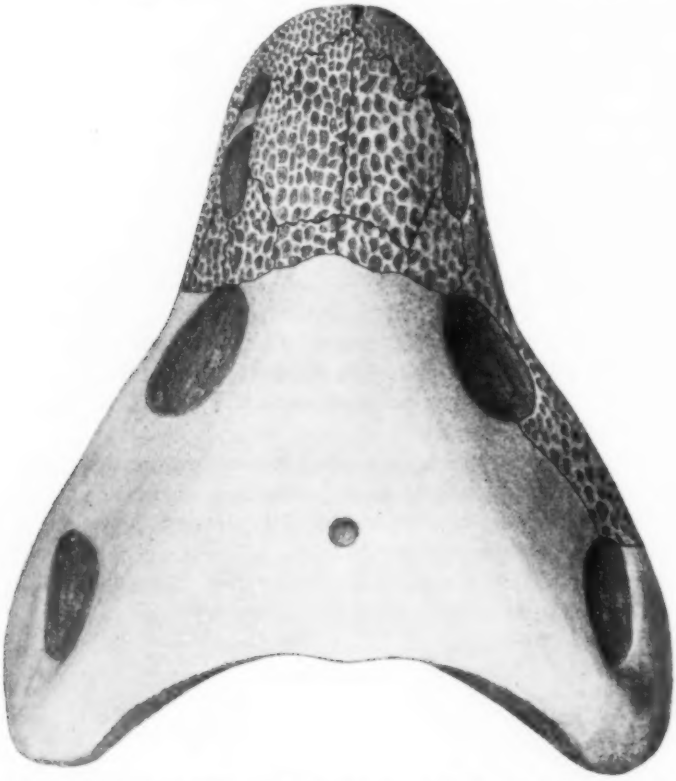

FIG. 1.—*Trematops thomasi* Mehl. Dorsal view of skull; four-fifths natural size. Lightly shaded portions represent restoration.

are separated for a short distance at their anterior ends by a thin intrusion of matrix, but posteriorly they are clearly united, as are the nasals. The writer considers this slight separation of the premaxillae an accident of preservation like the more marked separa-

tion of the rami of the mandible at the symphysis, and not indicative of a vestigial unpaired opening.

The antorbital and narial vacuities are united. These combined openings are, in a general way, similar to those of the type of *Trematops*. They are relatively much smaller in the present specimen, however, 31 mm. long and 12 mm. wide. The anterior margins of the openings are about 16 mm. from the tip of the rostrum and near the lateral margins of the skull. The planes of the openings are directed

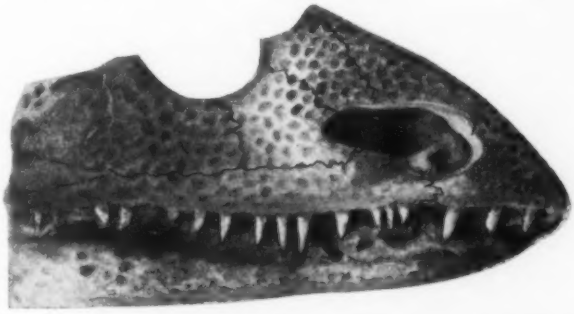

FIG. 2.—*Trematops thomasi*. Lateral view of skull; four-fifths natural size

chiefly out, slightly up, and forward. While the upper and lower borders are essentially parallel, there is a slight constriction at about mid-length. Immediately in front of this constriction there is directed in and forward into the narial passage, from the lower margin of the opening, a delicate, curved bone to be described more fully later.

The orbits are directed out, very slightly up, and forward. They are essentially circular in outline, perhaps a little longer than high. They measure 28 mm. in the antero-posterior direction. The bar separating the orbit from the antorbital vacuity is 15 mm. wide.

In the accompanying drawing (Fig. 1) the writer has indicated an opening in the temporal region, a part of the skull not preserved. Its presence and position is based in part on the condition described by Williston. There is, however, some evidence of the opening to be found in the present specimen. At a distance of 25 mm. back of the orbit, where fracture terminates the skull, there is a marked inward

curve of the surface of the skull to what seems to be a slight length of finished margin.

BONES OF THE UPPER SURFACE

The premaxillae form a narrow band about the anterior border of the skull. Along their line of union the length is 10 mm. Posteriorly each premaxilla is forked, the two prongs forming the anterior border of the nares.

FIG. 3.—*Trematops thomasi*. Details of the combined antorbital-narial opening to show development of "turbinated" bone; twice natural size.

The maxillae are very narrow. The greatest width, near the anterior end, is not over 9 mm. The anterior end of the maxilla forms approximately the middle third of the lower margin of the antorbital-narial vacuity.

The turbinated (septomaxilla?) bones are definitely recognized in this specimen. Of *T. milleri* Williston stated: "A flattened or concave bone is seen in the right fossa [the antorbital-narial vacuity], directed obliquely backward. It may be a turbinated bone."[1]

In the present specimen the general form, position, and relations of this delicate bone are shown in both nares. On the right side the matrix has been completely removed to show the details as indicated in the accompanying drawing (Fig. 3).

The "turbinated" bone is 4 mm. wide and something over

[1] S. W. Williston, *op. cit.*, p. 641.

14mm. long. It articulates, apparently by suture, with the anterior end of the maxilla at the premaxilla union. It extends up and forward a very slight distance in the plane of the face to an abrupt curve inward. The incurved portion parallels the anterior border of the internal nares a little above and forward of the openings margin. The facial part of the bone is minutely pitted.

The nasals are about twice as long as wide. The greatest length, along the median line, is 45 mm. The posterior ends meet the frontals in an almost straight transverse suture.

The prefrontals are about as long as wide. They form the upper posterior borders of the antorbital vacuities and the anterior borders of the orbits.

The lachrymals form the lower anterior borders of the orbits and the posterior borders of the antorbital vacuities.

The jugal and the quadratojugal are represented in part only.

THE PALATE

It has not been possible to separate the mandible from the skull, but the matrix has been removed in such a way as to show essentially all of the palate that has been preserved. In most cases the sutures are distinct, but in others there is some doubt. The writer has indicated these conditions with suitable symbols in the accompanying drawing (Fig. 4).

The striking feature of the palate is the unpaired opening at the anterior end of the prevomers. The broad symphysis of the mandible conceals the anterior part of this opening so that its shape and size are somewhat in doubt. The posterior and postero-lateral boundaries are distinct, however, as indicated.

The nares, close to the margins of the skull, are 20 mm. long and 10 mm. wide.

SEPARATE BONES OF THE PALATE

While the premaxilla-maxilla union is evident, the extent of neither of these two bones on the palate can be determined.

The prevomers form most of the lateral borders of the internal nares and the postero-lateral borders of the unpaired median opening described above. Lengthwise these bones are sharply ridged so

that along their union at the median line there is a marked linear excavation leading to the unpaired opening at the anterior end.

The palatines are apparently long and narrow, extending from the posterior border of the nares to the anterior border of the sub-

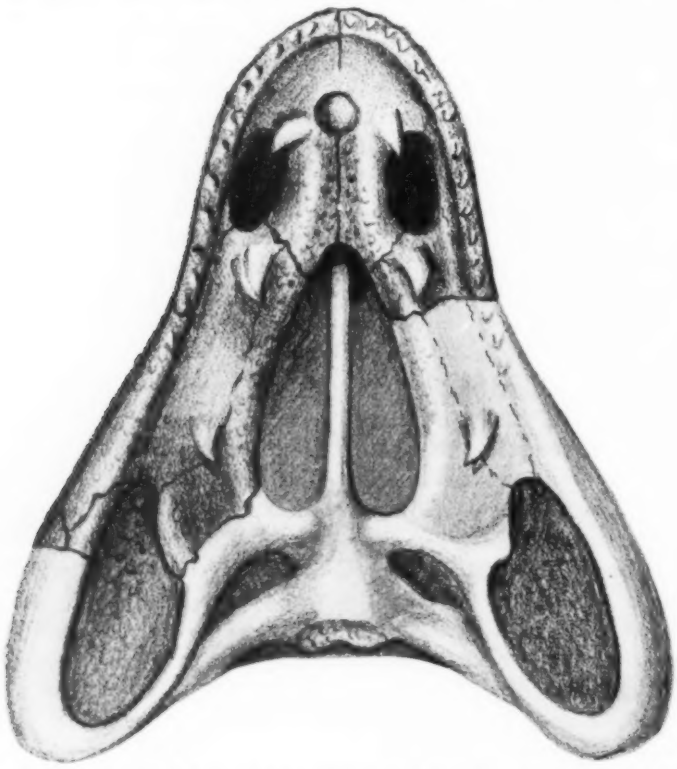

FIG. 4.—*Trematops thomasi*. Palate view of skull; four-fifths natural size. Lightly shaded portions indicate restoration.

temporal openings. If the relations are properly determined, the palatines are excluded from the interpterygoid openings by the pterygoid bones.

Only a small part of the anterior end of the left pterygoid is

preserved. On the right side, however, this bone seems nearly complete, lacking only a little of the posterior end. It extends back 43 mm. along the lateral border of the interpterygoid vacuity from near the anterior end of this opening, where it joins the prevomer.

The parasphenoid is not preserved. The writer has shown it in the accompanying palate view, however, because of the apparent section through the parasphenoidal rostrum at the level of the anterior end of the frontals as indicated in Figure 5.

FIG. 5.—*Trematops thomasi*. Partial section of skull at level of anterior end of frontals to show parasphenoidal rostrum; twice natural size.

THE TEETH

Each premaxilla bears six teeth, all about the same size. None is over 8 mm. in length and 3 mm. in diameter at the base. All are slender and slightly recurved.

On the maxilla there are fifteen teeth, possibly one or two more, very similar to those of the premaxilla. They are round in cross-section, sharp pointed, slender, and slightly recurved. A few, near the center of the series, are as much as 10 mm. or 12 mm. in length. They are shorter at the ends of the series, not over 4 mm. long.

At the anterior end of each prevomer, between the anterior end of the internal nares and the median vacuity, is a sharp, conical, slightly recurved tooth about 15 mm. long.

Just behind the internal nares, at the inner-anterior end of the right palatine, are two conical teeth, 18 mm. long, similar to those of the prevomers. They extend almost to the lower margin of the mandible. They are closely crowded together at the base and lie in an antero-posterior line. The left side of the palate is broken away at about the point where these teeth should be, and only one is preserved on this side. A similar tooth is found at the posterior end of the palatine. Its length is 11 mm. The large teeth of both palatines and prevomers have the enamel complicately infolded.

Closely spaced over the arched or excavated portion of the prevomers, especially along their ridges, are many minute teeth,

most of which have been destroyed in the preparation of the specimen.

Along the inner margin of the pterygoid are numerous small teeth similar to those of the prevomers.

THE MANDIBLE

Few details of the lower jar are determinable, although the right ramus apparently lacks only a short section at its posterior end. About the anterior third of the left ramus is present. The writer is not able to locate the sutures between the component bones with any degree of certainty. Apparently the splenial extends forward along the lower-inner margin to take part in the symphysis. At the posterior end of the preserved part of the right ramus, apparently a section through the coronoid region, the depth is 29 mm.

The marginal dentary teeth are partly exposed. They are similar to the marginal teeth of the skull in size and number.

PETROLOGICAL ABSTRACTS AND REVIEWS

ALBERT JOHANNSEN
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ADAMS, L. H., AND WILLIAMSON, E. D. "The Compressibility of Minerals and Rocks at High Pressures," *Journal Franklin Institute*, CXCV (1923), 475–529.

The compressibilities of a number of minerals and igneous rocks have been determined under hydrostatic pressures up to 12,000 megabars, corresponding to a depth of 40 kilometers below the surface of the earth. The method used has already been shown to yield consistent results for metals and other solids. According to this method the specimen is completely surrounded by a liquid, kerosene, and is subjected to pressure in a thick-walled steel bomb.

The compressibility of the minerals usually falls off slightly as the pressure is increased. For the less compressible minerals, however, the change in compressibility is so small as to escape detection by the present method, the precision of which corresponds to about 0.01×10^{-6} per megabar, that is, to 1 per cent of the total compressibility of the less compressible minerals.

The results show that, except for very low pressures, the compressibility of a rock may be calculated directly from the known compressibility of the constituent minerals, provided that the rock is holocrystalline. In general, the compressibility increases with increasing basicity, that is, with decreasing silica content. Quartz and metallic iron may be considered to stand at the two extremes as regards the compressibility of igneous rocks. At 10,000 megabars the compressibility of a typical granits is about 1.9×10^{-6} per megabar, and that of a typical gabbro is about 1.2×10^{-6}.

From the ratio of the velocities of the two kinds of waves transmitted through the earth and from the known elastic behavior of compact rocks it is believed that the value of Poisson's ratio for rocks at moderate or high pressures is very close to 0.27. From this value and from the measured compressibility the rigidity of a number of typical rocks is calculated. The rigidity of a typical granite at 10,000 megabars is 0.3×10^{6} megabars; that of a typical gabbro is 0.5×10^{6}; and that of an ultra-

basic rock, e.g., a dunite, is 0.6×10^6. The rigidity of the earth as a whole, which is probably near that of steel (0.9×10^6), is higher than the value for the most rigid silicate rock but doubtless the rigidity of a basic or ultra-basic rock is raised enough by pressure corresponding to a few hundred miles of rock to yield the required value.

From the values of the bulk modulus (the reciprocal of the compressibility) and of the rigidity, the velocities of the two kinds of waves transmitted through the earth are calculated for the various types of rocks. With increasing basicity of the rock, the velocity of the longitudinal vibrations increases steadily from the value of granite, 5.6 km./sec., to that of dunite, 7.4 km./sec., but is lower, 6.0 km./sec., for metallic iron. The initial velocity of the longitudinal vibrations is usually taken to be a little above 7 km./sec. This corresponds to a gabbro or to a pyroxenite, and furnishes an indication of basic or ultra-basic material at a relatively small depth below the surface of the earth. (Quoted from the summary.)

ALLEN, E. T., "Chemical Aspects of Volcanism, with a Collection of the Analyses of Volcanic Gases," *Journal Franklin Institute*, CXCIII (1922), 29–80; 11 pages of analyses.

The original volcanic gases can be traced back to the igneous rocks. Water is probably the most important of them.

The original volcanic gases are generally changed in composition by the time they reach the point of collection; in some cases they probably lose a portion of the strong acid gases; in most cases they become diluted by steam from surface water and by the atmospheric gases.

In some volcanic emanations the relations between the inert gases point to an atmospheric origin for these particular constituents: in others the inert constituents must either be of deep-seated origin or their original atmospheric relation has been changed by selective solubility in the magma.

Deville's laws respecting the variation in the composition of volcanic gases with the distance from an eruptive center or with passing time are not supported by the great body of evidence.

There is evidence to show that a more or less abrupt evolution of gas from the magma occurs during crystallization, but it needs further support.

Chemical energy from shifting equilibria may have a considerable influence in prolonging the life of an eruption, but not in initiating or rejuvenating volcanic activity. Surface combustion in particular instances is probably an important factor in keeping up temperature.

Secondary volcanic explosions of great violence are undoubtedly produced by the access of surface water to hot volcanic ejecta. The primary explosions, according to the best evidence, are the results of pressure from magmatic gases, not the result of chemical action. (Quoted from the summary.)

ALLEN, E. T., AND ZIES, E. G. "A Chemical Study of the Fumaroles of the Katmai Region," *National Geographic Society Technical Papers*, Katmai Series, No. 2 (Washington, 1923), 75–155; 28 figs.

The authors believe that the fumaroles of the Katmai region are fissure fumaroles. In 1919 the temperature ranged from less than 100° to about 650°, but it is believed that fumarolic activity is declining at an appreciable rate. Steam is the principal component of the gases, and forms from 98.65 to 99.85 per cent by volume of the samples collected. The water from which it is derived is thought to be largely of surface origin. Among the other gases present are HCl, CO_2, H_2S, N_2, HF, and sometimes CH_4. The heat is not derived from the oxidation of the gases by atmospheric oxygen, nor is it generated in the surrounding pumice by this means. No combustible gases burn at the surface. Deville and Fouque's statement that magmatic gases are everywhere uniform and that their composition is subsequently modified by no variable agency except temperature is held untenable.

ASKLUND, B. *Petrological Studies in the Neighborhood of Stavsjö at Kolmarden: Granites and Associated Basic Rocks of the Stavsjö Area* (Dissertation, University Upsala). Stockholm, 1925. Pp. 122; 33 figs.; 1 map.

The granites of the region described form a broad band running northeast and southwest and cover a large part of the area. There are three principal granite massifs of similar rocks, and each is the youngest member of the differentiation sequence in its district. So-called "basic rocks" occur in the southern part of the area, and consist of noritic gabbro and quartz diorites. Many of the rocks are analyzed and calculated into norms, but in general where chemical analyses are given there are no modal percentages, and where volumetric analyses are given there are no chemical analyses. The differentiation in the region is thought by the author to be due to limited miscibility—liquation.

BANCROFT, J. AUSTEN, AND HOWARD, W. V. "The Essexites of Mount Royal, Montreal, P.Q.," *Transactions Royal Society of Canada*, XVII (1923), 12–43; 1 fig.; 3 plates.

The construction of the Canadian National tunnel through Mount Royal afforded a continuous rock section 3.1 miles in length. It was found that the greater part of the igneous mass of the mountain is essexite, which is the oldest intrusion in the area. This was followed by the intrusion of dikes of bostonite, tinguaite, camptonite, and monchiquite. A shattering of the essexite was followed by an intrusion of nephelite syenite, both in dikes and in mass. Another intrusion of dikes of camptonite and maenaite followed, and then came an extensive intrusion of camptonite which forms the matrix of the essexite breccia which underlies the western summit of Mount Royal. Finally nephelite syenite dikes were followed by two series of camptonite dikes.

The rocks here called essexites "include gabbro-diorites and gabbros, diorites, wherlites, and pyroxenites." They are all relatively high in soda, but, of sixty or more specimens examined, only one showed nephelite. They are placed in the essexite group because they show "relatively large, though variable, proportions of normative nephelite which is characteristic of rocks belonging to the essexite group." But when the name essexite was given by Sears to a certain group of rocks from Essex county, Massachusetts, in 1891, "normative nephelite" had not been invented. It seems to the reviewer that chemical modifications of rock definitions which were originally based upon mineral composition are undesirable, and that *omnium gatherum* names, such as essexite, should not be used.

Among the other rocks described are andesite gabbro, diabase gabbro, wehrlite, pyroxenite, and montrealite. There are many new chemical analyses, and, a feature that should be more widely followed, there are analyses of some of the component minerals. While in the literature of mineralogy there are many analyses of rock-forming minerals, yet the number of such analyses from rocks whose mineralogical and chemical compositions are also given, is small. Modal analyses are given of eleven rocks, and, the reviewer notes with pleasure, they are classified in his system. Although in some cases the kind of plagioclase is not stated in the description, the classification of eight rocks, in 3316 and one each in 3216, 417, and 4211, determines the exact composition.

Another interesting feature of the report is the complete description of the alteration of the olivine essexite. This is traced through four stages, and chemical and volume changes are calculated.

REVIEWS

The World in the Past. By B. Webster Smith. London: Frederick Warne & Co., 1926. Pp. 355, 3 plates. 10*s.* 6*d.*

The stated object of this book is to give a concise account, in simple and non-technical language, of some of the wonderful things that are recorded in the great stone book of the earth. A good selection of material, an interesting manner of presentation, and some striking illustrations, many of them in color, combine to achieve this end. For the professional geologist the chief value will lie in the many interesting details which it will probably add to his store of information. The facts have been drawn from many parts of the globe.

Unfortunately, however, the interpretative side falls far behind the descriptive. In many important respects the book seems decidedly behind the times. For the origin of the earth the author follows Laplace; for the origin of folded mountains, he follows Rev. O. Fisher. As to the condition of the interior of the earth, he states, on page 27: "On the ground of general probability . . . . it has been inferred that at no great depth—certainly under 50 miles, and possibly at less than half of that—all substances known to us must be in a molten or gaseous condition." Terrestrial formations such as the Old Red sandstone of Scotland, the Newark series of the eastern United States, and a large part of the non-marine Tertiary beds in general are treated as lake deposits in the main. Too bad that the great piedmont alluvial plain deposits, so striking in some parts of the world, remain so long unappreciated by many geologists of other regions.

But in spite of these shortcomings, the reviewer recommends this book for its information and its interest. Many structure sections in color, as well as colored views and restorations of ancient animals, are a notable and praiseworthy feature of the book.

R. T. C.

Illinois State Geological Survey, Bull. 45, "Structural Reconnaissance of the Mississippi Valley from Old Monroe, Missouri to Nauvoo, Illinois." By FRANK KREY. Urbana, Illinois, 1924. Pp. 86, 18 plates.

Missouri Bureau of Geology and Mines. Vol. XVIII, 2d series. Rolla, Missouri, 1924. Pp. 86, 18 plates.

Two state surveys present the results of a co-operative reconnaissance survey of the oil structures and stratigraphy in a strip about fifty miles wide along both sides of the Mississippi River. The chief purpose of the survey is to give an idea of the larger regional structures, rather than local and minor disarrangements of the beds.

The most important contribution is the large-scale contour map which indicates outcrops as well as the principal structural features. The most pronounced structure of the region is an anticlinal fold which extends from Grafton, Illinois, northwest across the Mississippi to southern Marion County, Missouri. This fold the author calls the Lincoln anticline. Bounding it on the south is the well-known Cap-au-Grès fault. The next most important structure is the Pittsfield-Hadley dome, which has already been described in a report of the Illinois survey.

Except for small amounts of gas obtained in the Pittsfield-Hadley dome, this area is at present unproductive of oil or gas. But in the opinion of the author there is good evidence that oil has been present and may be present still in minor quantities. The most favorable places for accumulation are pointed out.

In referring to the Devonian of Missouri, Krey disregards the established classification, assuming that the Devonian of Iowa and Missouri are equivalent. On Plate II Krey shows the Hannibal shales overlying the Kimmswick limestone in St. Charles County, Missouri. But Branson claims that there is no evidence of Hannibal outcropping in this county. He believes that the formation which Krey calls Hannibal is really the Sylamore (equivalent to the Grassy Creek, farther north). There are other differences of opinion which might be noted.

D. G.